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Groundwater Yield Modeling in the Fractured Bedrock Aquifers of the Blue Ridge  
Physiographic Province, Watauga County, North Carolina

A Thesis  
by  
Williams Coker Gandy

Submitted to the Graduate School  
Appalachian State University  
in partial fulfillment for the degree of  
MASTER OF ARTS

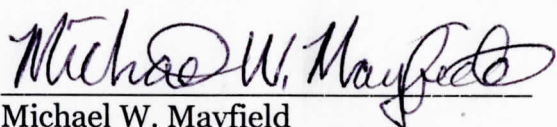
August 2009  
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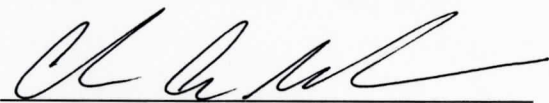
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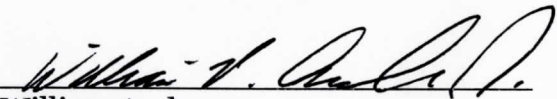
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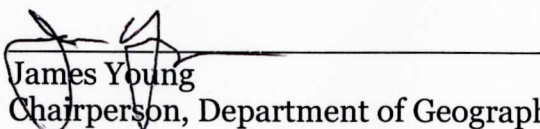
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## ABSTRACT

Groundwater Yield Modeling in the Fractured Bedrock Aquifers of the Blue Ridge  
Physiographic Province, Watauga County, North Carolina  
(August 2009)

Williams Coker Gandy, B.S. Appalachian State University

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Groundwater is a commodity that is used by the majority of residents of Watauga County, North Carolina (NCDENR 2001; NC Cooperative Extension 2001). The fractured bedrock aquifers that house the water that these residents access by wells have long been known to be highly heterogeneous and thus problematic at times for locating ideal areas to drill productive wells. In 1967, the United States Geologic Survey (USGS) published a paper written by Harry LeGrand (LeGrand 1967) that predicatively modeled groundwater availability for the Blue Ridge and Piedmont Provinces in North Carolina. The model used various categories of topographic position and regolith thickness to assess how productive (in gallons per minute) a potential site would be. The language used for describing LeGrand's (1967) topographic categories is familiar but vague. This study uses digital elevation model (DEM) derived surfaces to quantify and replicate LeGrand's (1967) topographic categories in the Geographic Information System (GIS) environment and to test the model against a database of wells in Watauga County.

Lineaments are surface expressions that are thought to have geologic or stratigraphic phenomena associated with them and are commonly used in groundwater studies in these types of aquifers. Lineaments were digitized in the GIS environment to compare lineament techniques to that of LeGrand's (1967).

Linear regression using a USGS well database showed that neither LeGrand topographic points nor lineaments were significant explanatory variables with respect to well yield. Instead, 51.4% of well yield variation was explained by shallow well depths and higher sequences of overlying material above the bedrock. A second regression using stratified random wells with regard to well depth revealed that shallow well depths and lower slope values explained 30.0% of the yield variation. A regression model integrating lineaments was run in the amphibolite lithology for Watauga County and found only shallow well depths as a significant explanatory variable at 27.1% of yield variation.

Finally, using the mean well yield of all of the various categories of the DEM derived topographic attributes, a raster map of groundwater likelihood was created for Watauga County. MOD2 does not predict well yields, but rather gives a general idea of the spatial extent of groundwater hotspots for the county. This procedure allows for undrilled areas in the county to be quickly assessed for groundwater likelihood, and could easily be replicated for any study area.

## DEDICATION

For my parents and brother whom I love so very much, who have always loved and supported me in all endeavors. Thank you for being the model for what is good in life. For my great friend and mentor Mike Mayfield who has always guided me through my geographic explorations and with whom I have shared many great experiences and laughs. For the Departments of Geography and Planning, and Geology whose faculty helped to sculpt my outlook on this vast world. For Caroline Poteat, who loved, supported and tolerated me through my graduate education and beyond.

## TABLE OF CONTENTS

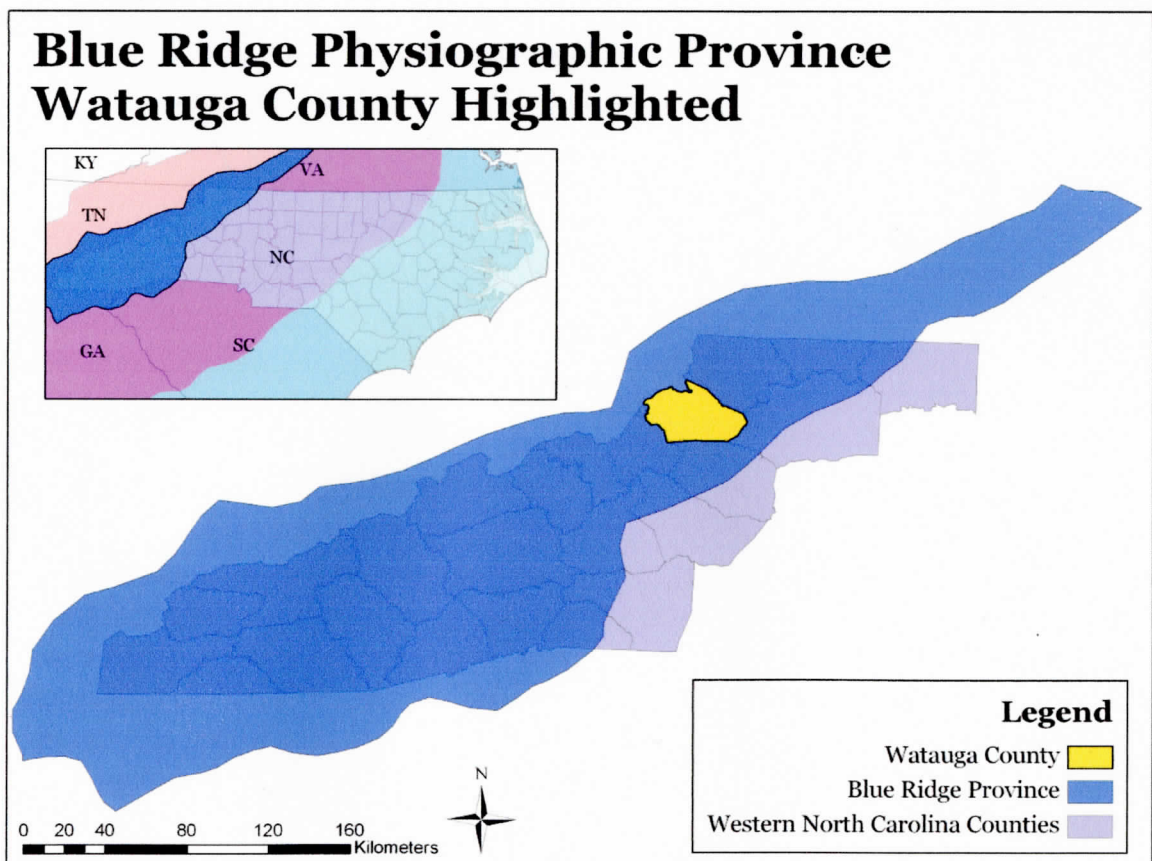
Abstract.....	iv
Dedication.....	vi
Chapter 1: Introduction .....	1
The LeGrand (1967) Model.....	3
Chapter 2: Literary Discussion.....	9
Introduction: Evolution of LeGrand's Model over 30 Years.....	9
Lineaments.....	10
Lineament Techniques.....	14
Chapter 3: Geomorphometric Analysis for the LeGrand Model .....	20
Introduction: Defining Landforms.....	20
Background .....	23
Methods.....	26
Model Implementation .....	32
Geomorphometric Results and Discussion .....	36
Geomorphometric Analysis Conclusions .....	39
Chapter 4: The Watauga Study Area and Lineament Procedures .....	41
Introduction – The Watauga Wells Database .....	41
Field Methods .....	41
Lineament Procedures and Methods.....	43
Using ArcView Avenue Scripts to Aid in Lineament Analysis .....	46
Chapter 5: Statistical Analysis.....	50
Introduction .....	50



Watauga County Linear Regression Results .....	53
Stratified Random (Well Depth) Regression.....	56
Analysis in the Amphibolite Region of Watauga County .....	59
Statistical Conclusions .....	62
Chapter 6: Discussion.....	64
Raster Modeling Topographic Categories .....	64
Statistical Modeling .....	66
Regression Model Integrating Lineaments in the Amphibolite Region .....	69
Chapter 7: Final Analysis and Creation of MOD2.....	71
Chapter 8: Summary .....	76
Chapter 9: Conclusion .....	79
References.....	82
Appendix A .....	86
Appendix B.....	88
Appendix C.....	90
Appendix D .....	92
Appendix E.....	94
Appendix F.....	96
Biographical Sketch .....	98

## Introduction

Watauga County, North Carolina is in the portion of the state's counties that at least partly fall within the Blue Ridge Physiographic Province (Figure 1). Watauga, as well as the other counties in the North Carolina Blue Ridge region are home to about 12.45% of the state's population (US Census 2008). These scenic areas are a regular tourist destination for people within the region and beyond. Mountains all over the world are sources of "water, energy and biological diversity", and many fundamental human resources such as "minerals, forest" and "agricultural products and of recreation"(Ives, Messerli, and Speiss 1997, 2). Those facts paired make it easy to see that there is need for water for the inhabitants, industry and visitors of



**Figure 1. Watauga County, NC within the Blue Ridge Province.**



the Blue Ridge Mountain area. The region's population is increasing along with its popularity as a tourist destination and there is a current and increasing demand for water in the Blue Ridge Region of North Carolina. Most of the inhabitants of North Carolina, including Watauga County, live in rural areas that require a self-supplied water supply, and all of those residents draw their water from the ground (Heath 1980; NCDENR 2001). Though there is no current domestic self-supplied surface water intake (NCDENR 2001), that avenue for water use is quickly closed by municipalities' right to surface water intake on already low-flow, headwater streams. With that in mind the dominant form of water supply for the majority of residents in the Blue Ridge region will likely continue to be private groundwater wells.

Groundwater in Watauga County and throughout the Blue Ridge Physiographic Province has long been recognized as complex due to the heterogeneity of the region's fractured crystalline aquifers, which frequently occur in mountainous environments (Heath 1980; Seaton and Burbey 2005). Ralph C. Heath, a prominent hydrogeologist in North Carolina, described the region's aquifers as "the exact opposite of the homogeneous and isotropic media usually assumed in the development of ground-water flow equations" (Heath 1992, 619), (unlike aquifers made of a more porous and permeable medium capable of holding water within the rock matrix). The Blue Ridge aquifers' principle transmissive agents are the fractures that occur in the otherwise impermeable crystalline bedrock matrix, which Henriksen (2006) described as groundwater flow in rocks "with no intergranular porosity" (373). These fracture networks can form through exfoliation, by the unloading of overlying material through denudation, and/or by tectonic

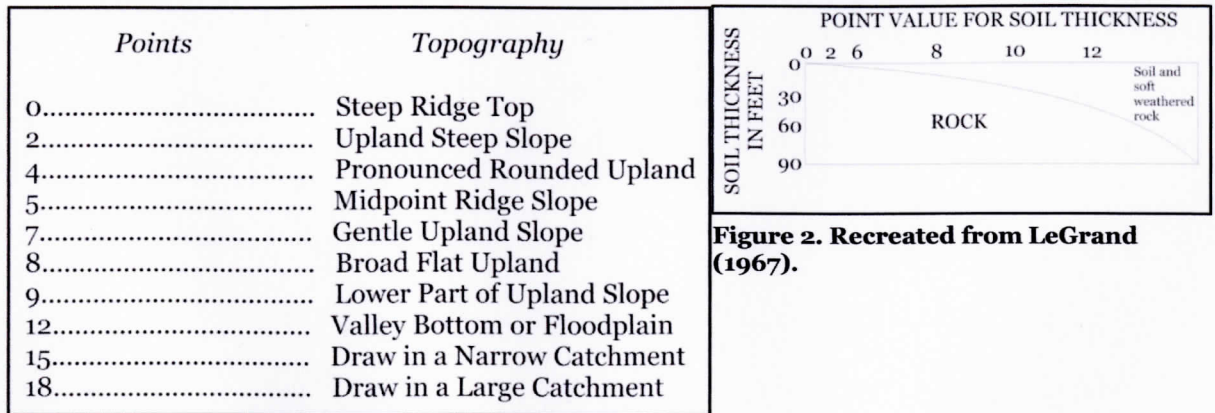
stresses. To further complicate the scenario, these environments are often found to have gone through multiple stages of orogeny and metamorphism (Seaton and Burbey 2005). The fractures and faults which serve as conduits for the flow of groundwater and its storage become more important when they occur at greater frequency, are larger, and intersect with other fractures. This suggests that the highest potential for significant groundwater yield is at a point where fractures intersect each other, as water is thus drawn from a larger area. Understanding the patterns associated with these criteria is paramount when trying to locate areas of high groundwater potential. With such great variability of geologic characteristics across the Blue Ridge, finding these patterns proves to be difficult.

#### *The LeGrand (1967) Model*

In 1967, Harry Elwood LeGrand developed a predictive groundwater model for North Carolina's Piedmont and Blue Ridge Provinces (LeGrand 1967). Although the paper, published by the United States Geologic Survey (USGS), made no direct reference to previous studies or data, LeGrand (1992) later stated that it was based on years of work prior to the 1967 report including discussions with well drillers, Mundorff's (1948) report on geologic hydrology in Greensboro, North Carolina, and a collaborative effort between LeGrand and Mundorff in 1952 that studied groundwater in Charlotte, North Carolina (Yin and Brook 1992b; LeGrand 1992).

The model is primarily based on the topographic position of the well in question and secondarily on the thickness of the regolith at the site (Table 1 & Figure 2). LeGrand (1967) deliberately simplifies an otherwise extended explanation of these parameters by stating: "High-yielding wells are common where thick residual

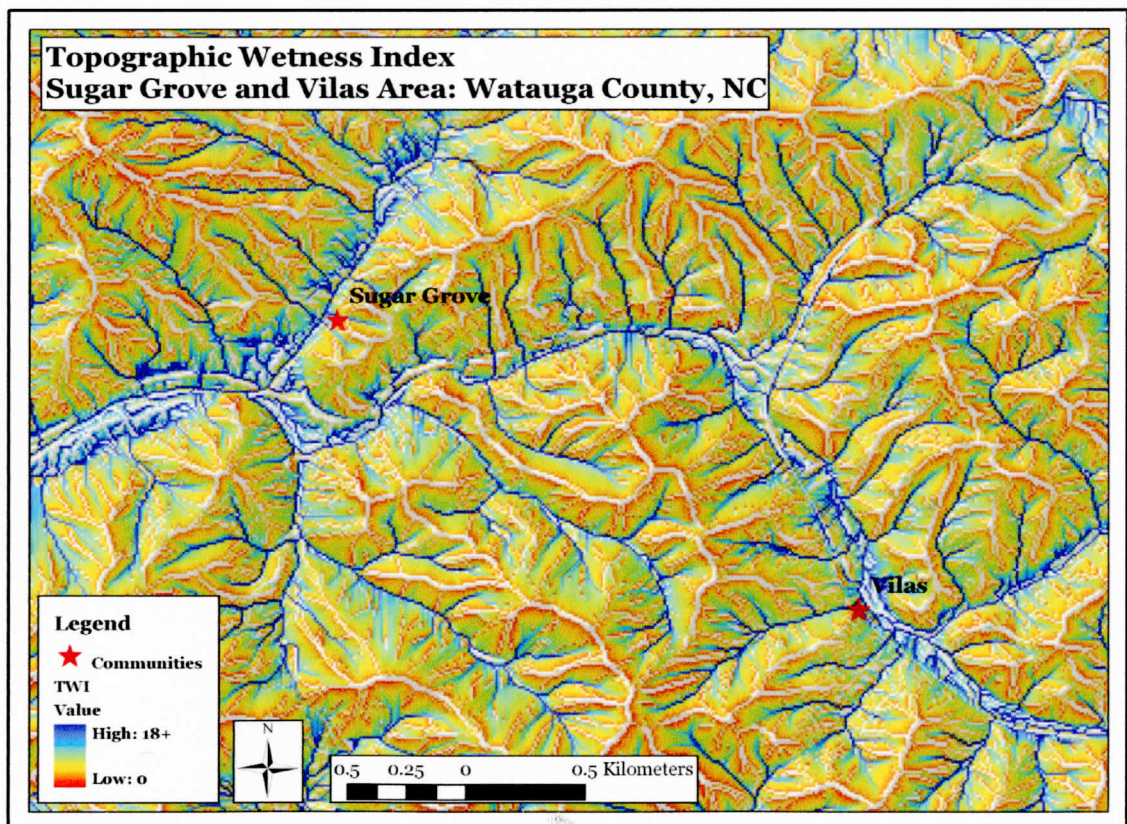




**Table 1. Recreated from LeGrand (1967).**

soil and relatively low topographic areas are combined, and low yielding wells are common where thin soils and hilltops are combined” (1). LeGrand (1992, 618) points out that fracture concentrations are typically found at topographic lows and the differential weathering and further enlargement of these fractures is what is thought to form these sags in the topography. The idea of topographic location with regard to fracture concentration goes hand in hand with how topographic attributes and position on the landscape dictate how much recharge is likely to infiltrate and perhaps recharge fractures (LeGrand 1967, 3). Beven and Kirkby (1979) describe a similar factor in their work based on the concept of the topographic wetness index (TWI). The index assigns a number to any point in a watershed based on the contributing area above the point and the local slope; higher values on the range of TWI values indicate areas that will become saturated first in a storm event (Beven 1997). Without the aid of a system similar to Beven and Kirkby’s (1979) work, the logic of LeGrand (1967) can be applied with geomorphometry’s influence on water movement. For instance, a convex shape such as a ridge, usually associated with steep grades, will shed or diverge precipitated water to another location down gradient. This will diminish the chance for infiltration and recharge. Conversely, a

concave shape like a draw (depression in a slope) will accumulate or converge water to its center, transporting greater amounts of water to a location potentially allowing for higher amounts of infiltration into the subsurface. This reasoning is similar to Beven and Kirkby's (1979) wetness index when assessing a watershed drainage structure and where the areas of the greatest saturation potential can be found (Figure 3). LeGrand (1967) rates areas associated with depressions and low grades favorably in his model with common, but vague, language with regard to groundwater. The TWI designates similar areas as favorable by quantitatively assessing the local topographic attributes with regard to vadose zone hydrology; the two ideas are different in their end result, but linked by the interaction of the vadose and saturated regions.



**Figure 3. Topographic Wetness Index (Beven and Kirkby 1979).**



If the setting in question is an upland drainage basin containing low order streams that upon confluence express a valley stream, generally the further down slope a location is, the greater the contribution of water will be to that area. As position on the landscape nears a stream located in a valley, the greater the amount of contributing area that point has, and the more recharge it will receive. These qualities lessen as the position changes to higher areas such as a ridge. This is the reason why LeGrand (1967) rated draws with large contributing areas, and valley bottoms so high in his model. The same trend in points changes in relation to similar topographic attributes in the TWI model.

The other facet of LeGrand's (1967) model was the regolith depth at the site, which the 1967 report referred to as "soil thickness" (LeGrand 1967, 2). Later work by Heath (1980, 30) describing the same model and hydrogeologic framework in North Carolina referred to this variable as "saprolite" or "residuum". When addressing the "thickness" variable in this work the term used will be "regolith" or all of the material above bedrock (Fairbridge 1968; Daniel 1989, A-6). The thickness of regolith at a given point is largely a product of its topographic position but can be variable enough to be treated as a separate consideration when analyzing groundwater recharge. The regolith covering the basement rocks' fractures acts as the sponge that potentially can hold groundwater and transmit it to the fractures it covers. A thicker sequence of regolith covering the site increases its holding capacity, thus increasing its potential for recharge. Those areas with the thickest sequences of regolith are also favored and rated highly in the LeGrand (1967) model (Figure 2). LeGrand's (1967) table for calculating the regolith points is fairly general, and the

hydrologist working in the field would be only making an educated guess at the thickness of regolith at the site. This uncertainty is addressed by LeGrand (1967, 4) as acceptable, and differences in point totals between field practitioners in the range of about 5 points “would not be misleading” with respect to the predicted yields.

LeGrand (1967) describes topographic position as the “next best approach” to forecast well yield in an otherwise “unpredictable” hydrogeologic environment (1967, 1). With the topographic position in mind, one could rate the area per the model scoring system that was included in the report (1967, 2). When the final score was assessed, a table referenced (Table 2) the score and gave an average yield to be expected from the well drilled, and the percent chance of yielding 3, 10, 25, 50, or 75 gallons per minute (gpm) as was indicated by Table 2. LeGrand has not published the data used to develop his model (1967) and thus makes the model difficult to assess.

Given the popularity and widespread use of LeGrand’s techniques, this study will assess the LeGrand (1967) hydrologic model in the Blue Ridge Province with modern geographic information system (GIS) techniques that could be replicated completely by any user, and compare the results with newer alternative techniques.

Total points of a site	Average yield (gpm)	Chance of success, in percent, for a well to yield at least—				
		3 gpm	10 gpm	25 gpm	50 gpm	75 gpm
5	2	48	18	6	2	—
6	3	50	20	7	3	—
7	3	55	25	8	3	—
8	4	55	30	11	3	—
9	5	60	33	12	4	—
10	6	65	40	15	5	—
11	7	70	43	19	7	—
12	9	73	46	22	10	—
13	11	77	50	26	12	—
14	12	80	52	30	14	—
15	14	83	54	33	16	—
16	16	85	57	36	18	—
17	17	86	60	40	20	12
18	20	87	63	45	24	15
19	23	88	66	50	25	18
20	26	89	70	52	27	20
21	28	90	72	54	30	22
22	31	91	74	56	35	24
23	34	92	76	58	38	26
24	37	92	78	60	40	29
25	39	93	80	62	43	32
26	41	93	81	64	46	36
27	43	94	82	66	48	40
28	45	95	83	68	50	42
29	46	95	84	71	53	44
30	50	96	87	73	56	47
30+	50	97	91	75	60	50

Table 2. (LeGrand 1967).



## **Literary Discussion**

### *Introduction: Evolution of LeGrand's model over 30 years*

After the initial report was published, the general hydrologic model LeGrand described in 1967 was and remains the widely accepted idea of how groundwater functions in the Blue Ridge as well as the Piedmont (Heath 1980; Daniel, Smith, and Eimers 1997; LeGrand 2004; Seaton and Burbey 2005). In recent years, there has been discussion (Seaton and Burbey 2005) as to how well the general hydrologic model of the Blue Ridge and Piedmont Provinces works for the Blue Ridge. Daniel, Smith, and Eimers (1997) discussed the grouping of the two different regions for hydrologic analysis due to how similar the rock types are; those being mostly metamorphic and igneous bodies. Seaton and Burbey (2005) argued that the unique structural controls and shallower sequences of regolith found in the Blue Ridge make this combination too general.

The 2005 study by Seaton and Burbey found that thrust faulting in their study area in Southern Virginia was the controlling variable for “two hydraulically distinct aquifers” (312). Whereas the compressive forces exacted on the North American plate have resulted in textbook folding in the Ridge and Valley Province immediately west of the province, these forces express themselves as thrust faults in the Blue Ridge. This faulting was found to be a crucial groundwater resource and is common regionally throughout the Blue Ridge (Seaton and Burbey 2005; White and Burbey 2007). The importance in relation to groundwater comes from the conductive fractures that thrust faults can create at 50-300 meter depths (Seaton and Burbey 2005, 312). The study named this deep thrust faulting as a pertinent variable and

went against the LeGrand model's suggestion of ceasing drilling at 300 feet (91.44 meters) in most cases (LeGrand 1967, 5). Seaton and Burbey (2005) found that significant yields may be found at greater depths than is usually accepted. Daniel found this to be true as well in his statistical study of the Piedmont and Blue Ridge Provinces with regard to well yield, and attributed the idea to stop drilling at around 300 feet to cultural bias (1989, A26).

In the case of the Seaton and Burbey (2005), the thrust faulting and its hydrogeological significance was determined by borehole geophysics and electrical resistivity profiles (302). This method of finding structural control stress in the subsurface is a costly one in that it involves either drilling a borehole or conducting time consuming field research at existing wells. Both methods require an expert to interpret the data; these field techniques are certainly not applicable to the resident looking for a cheap way to site a well. However, Seaton and Burbey (2005) advocated for new methods of groundwater exploration and were also able to extrapolate their findings throughout the Blue Ridge because of the "ubiquitous" thrust or en echelon faulting in the region (302), but that is not to say that every thrust fault is a conduit for large amounts of water, as it may very well be dry or unsustainable for prolonged use. Some thrust faults can even serve as aquicludes, especially when slickensides are present (William Anderson, Appalachian State University, April 2009, Interview)

### *Lineaments*

Faults, joints, fractures and other geologic phenomena often express themselves at the earth's surface as a lineament, which is defined as a perceived linear, continuous figure that is thought to be associated with a stratigraphic or

geologic structure (Kim, Lee, and Lee 2004). By this definition, thrust faults may express themselves as lineaments through other phenomena such as streams and valley segments, aligned surface depressions, linear vegetation patterns or abrupt topographic changes such as an escarpment or the precipitous edge of a mountain mass (Lattman 1958; Kim, Lee, and Lee 2004). Aligned linear surface expressions are delineated as lineaments such as straight valley segments, topographic sags, or as linear ridge lines. That leaves the surface manifestation of lineaments open to a swath of geographic and geologic features that may or may not be telling with regards to potential groundwater. When fractures are larger, more numerous, and intersect, there is an easy argument to be made that the potential for groundwater in these areas is higher. Larger, more hydrologically appealing fractures may express themselves on the surface of the earth as a lineament.

Hydrologists often rely on maps of lineaments to indicate favorable conditions for well drilling. Various studies (Neves and Morales 2007; Verbovšek and Veselic 2008) have examined groundwater occurrence with relation to lithologic boundaries or inferred fracture areas such as proximity to streams, and these areas are often delineated as a lineament zones. Studies in the Blue Ridge Mountains of the Eastern United States and from around the world have repeatedly examined lineaments and the role they play in understanding groundwater in fractured crystalline bedrock environments (Magowe and Carr 1999; Lachassagne et al. 2001; Mabee, Curry, and Hardcastle 2002; Henriksen 2003; Chandra et al. 2006; Adepelumi et al. 2006; Neves and Morales 2007); these and other lineament intensive studies have found



varying rates of success (Mabee, Curry, and Hardcastle 2002; Magowe and Carr 1999; Sander 2007).

The ability to accurately predict where potential groundwater would occur in high quantities for large swaths of territory is an attractive idea for anyone interested in water resources in these mountainous hydrologic scenarios. Yin and Brook's (1992a) paper *The Topographic Approach to Locating High-Yield Wells in Crystalline Rocks: Does It Work?* was a challenge to the LeGrand (1967) model. The intent of the work was to statistically analyze simpler LeGrand (1967) topographic categories. For example the category of "Hills" from Yin and Brook (1992a) accounts for all LeGrand's (1967) slope categories such as, "Upland Steep Slopes", and "Midpoint Ridge Slopes". Yin and Brook (1992a) then contrasted LeGrand's (1967) topographic technique with distance to lineaments the researchers interpreted from aerial photos. The paper concluded that their topographic categories only explained 0.3% of the variability in their regression model for well productivity. The distance to lineament intersection variable explained 59.0% of the variability in their model. This led the authors of the paper to conclude that the LeGrand (1967) approach to finding large amounts of groundwater in this terrain should not be used; rather the authors' method of fracture (lineament) tracing was deemed the better system.

In the at times heated discussion section of the next issue of Ground Water, LeGrand (1992) described the Yin and Brook (1992a) technique as a "Bayesian" approach that used "faulty logic in a convoluted way..." (618). LeGrand (1992) then went on to describe how fracture tracing with regard to groundwater was in essence the same concept as the topographic approach he described in his 1967 report. His

explanation was that topographic lows or sags are the product of structural weakness and in these areas, and fractures were more numerous. So, by fracture tracing through lineament discernment, Yin and Brook's (1992a) high yielding wells were coinciding with the same exploitations of geologic structures that LeGrand was referring to in his earlier paper (LeGrand 1992). Ralph C. Heath was another author who responded to the Yin and Brook (1992a) paper. Heath (1992) commented on the methods that Yin and Brook (1992a) used, mainly on the lineament picks and implications drawn from them. Heath (1992) stated that some of the findings of Yin and Brook (1992a) were "surprising" (619), with regard to the low correlation they found between well yield and topographic position points, and the high correlation found between well yield and lineaments. Heath's point was that a typical lineament pick would be delineated in a linear depression or such as a draw or stream valley to use LeGrand's (1967) terms. If this were the case, strong positive correlations *only* between well yield and distance to lineaments, and none between topographic position points does not seem plausible. Yin and Brook (1992b) responded that lineament picks not only were discerned through topographic expressions, but in soil tonal variations largely interpreted from remotely sensed images. So Yin and Brook (1992b) argued that there were enough lineament picks that had no topographic expression to "dilute" the depression picked lineaments, making statistical analyses produce results that had no correlation between LeGrand's (1967) topographic categories and groundwater yield. Heath (1992) also raised the question of data selection. The 29 wells used for analysis were from a population of more than 250 wells (Yin and Brook 1992b, 620) and were selected based on the most reliable data

associated with these wells. Heath (1992, 619) implied Yin and Brook's (1992a) techniques of data selection were biased and not randomly selected.

Quite commonly, research such as Yin and Brook's (1992a) that using the technique of lineament tracing also incorporates an abbreviated version of the LeGrand (1967) model (Yin and Brook 1992a; Knopman and Hollyday 1993; Henriksen 1995, 2003; Lachassagne et al. 2001; Verbovšek and Veselic 2008). Generally, these topographic categories are found to be separated into aggregate categories such as "hilltops or ridges", "hills or slopes", and "valley bottoms and floodplains". While some reference the statistical findings of Yin and Brook (1992a) arguing against the topographic position idea, others find significant correlation for these broad swaths of topography. Henriksen (1995) found that of her topographic categories of fjord slopes, valley slopes, ridges and hills, valley bottoms and flatlands, there was a statistically significant difference between well yields in valley bottoms and those on valley or fjord slopes, and attributed this to the holding capacity of the overlying material, and how the geomorphic element of slope affects the attributes of runoff and infiltration. In later work Henriksen (2006) found that the topographic setting explained over 25% of the variation in her statistical model, with lineament density coming in fourth with 12.7% of the variation explained. The coexistence of "LeGrandian" techniques with lineament analysis returns to the idea LeGrand (1992) argued for, that high topographic scores (LeGrand 1967) are coincident with topographic lineaments.



### *Lineament Techniques*

Techniques and tools for discerning lineaments range from user interpretation of remotely sensed data products including aerial photography, Landsat Thematic Mapper (Landsat TM) images and Digital Elevation Models (DEMs), to trained computer algorithms that take some of the subjectivity out of the process (Sander 2007). A common approach to minimizing the inherently subjective lineament picks of a human technician is to employ multiple picks made by several people. The “agreement” of these lineament picks is considered to be a superior data product to use in these studies (Lattman 1958; Sander 2007). In Yin and Brook’s (1992a) study in the Georgia Piedmont, the researchers delineated lineaments using not only topographic lineaments, but those derived from soil tonal variations (Yin and Brook 1992b). Lineament discernment using soil tonal variation is explained and illustrated in Lattman’s (1958) article, which discussed the emerging use of lineaments. Others have used the more popular technique of delineating lineaments with satellite images such as Landsat TM (Magowe and Carr 1999; Sander 2007). Typically these studies utilize the Landsat TM satellite’s ability to pick up on discrete vegetation patterns and more importantly the changes in it. In this way lineaments are delineated where there is a linear vegetation change. Segment tracing algorithms have been used to automatically pick lineaments using a computer’s non-biased logic (Kageyama and Nishida 2004). Computer algorithms have also been developed to “clean up” the digitizing process from several GIS technicians’ lineament picks (Kim, Lee, and Lee 2004).



Lachassagne et al. (2001) discussed the use of a GIS and lineaments in groundwater exploration with their strengths and weaknesses in mind. They pointed out that the “discontinuous” or anisotropic nature of groundwater in these environments elude the pattern finding-capabilities of a GIS, but also point out that the general trends and integration of lineaments in analysis has shown to be successful in the past (Lachassagne et al. 2001, 570). Even with the limitations of a GIS, they continue to be used for finding potential areas of large scale fracturing, due to their ubiquity and capability to display and processes for a variety of environmental imagery. Many times digitizing lineaments on imagery is a technique used. After lineaments are identified, a researcher will query several aspects of them with regard to groundwater data is the role a GIS plays. Common query functions are distance to lineament, distance to lineament intersection, and lineament density etc. With fractured crystalline hydrogeology in mind, those categories of lineament characteristics and their proximity to a well is how researchers and scientists try to make some sense of high and low well yields.

The idea that lineaments may be just a part of explaining groundwater in these environments is becoming more common. Fractures identified as lineaments can be dry, lack an appropriate amount of overlying material for adequate recharge, or can be plugged by clay minerals that are more readily weathered away from and into the fracture itself as well as other areas (Banks et al. 1996). Banks et al. (1996) reviewed fractured bedrock hydrogeology with stress regimes in mind. They discussed the commonly considered regional tectonic stress in regions such as the Blue Ridge that is also referred to as “paleostress,” which as the name suggests is

responsible for the fracturing over the longest amount of time (Banks et al. 1996, 224). Paleostress patterns can be helpful to recognize and account for variations in yield, as suggested by Seaton and Burbey's (2005) work on thrust faulting's influence on high groundwater yields in the Blue Ridge. Banks et al. (1996) go on to discuss in situ stress from the vertical and horizontal directions which can affect the size and aperture of the fracture. In some researchers opinions these stresses (not paleostresses) are the primary causes of size and aperture (Banks et al. 1996, 227). This, of course, would affect the chance of a lineament being identified, and cognizance of various stress directions and azimuths would be helpful in these scenarios when identifying lineaments. According to Daniel (1989), the in-situ stress of lithostatic pressure is *thought* to decrease the aperture of vertical fractures to unusable secondary porosity levels at about 300 feet (91.44 meters), as is suggested in LeGrand's (1967) report. He suggests drilling to greater depths to achieve higher yield levels, as is stated by Seaton and Burbey (2005). In these cases, statistics and resistivity testing to measure depth to a fracture were employed to correlate high well yields; lineaments were not the method.

Mabee, Curry, and Hardcastle (2002) were in a unique position to correlate lineament picks using common techniques to actual water bearing fractures by way of studying the conductive fractures in a metamorphic bedrock tunnel being built by the Massachusetts Water Resource Authority. The coincident lineaments picked by three technicians were confirmed as largely unsuccessful and statistically insignificant when compared to the corresponding fractures' yield inside the tunnel. In fact, most of the water-bearing fractures with high flow rates were large scale and



not picked up as “major structural feature(s)” on the surface (Mabee, Curry, and Hardcastle 2002, 42), and most of the lineaments that were picked did not bear significant or measurable yield. The authors’ suggestion was to use lineament analysis in conjunction with other techniques such as LeGrandian topographic position, rock type, and the idea of proximity to a water body, which could be argued as falling under LeGrand’s concepts (LeGrand 1967).

Research on the subject of lineament contribution to well yield continues to be conducted, mostly without direct reference to LeGrand’s (1967) approach, and are pursued worldwide as a viable avenue for explanation of groundwater occurrence in fractured crystalline environments (Yin and Brook 1992a; Magowe and Carr 1999; Daniel 1990; Lachassagne et al. 2001; Mabee, Curry, and Hardcastle 2002; Adepelumi et al. 2006; Chandra et al. 2006; Henriksen 2006; Neves and Morales 2007). A conclusion to be drawn from the interest in lineaments is that they are relatively easy and cheap to produce with the aid of a GIS for a wide swath of area. But the ease of identifying lineaments and using them as a criterion for groundwater models comes with the price of uncertainty. Lineament picks will coincide with highly conductive alluvial valleys as well as the barest of ridge tops; even a lineament that is not a valley, ridge, or depression could be expressing a geologic structure that may not be hydrologically significant (Sander 2007). According to Seaton and Burbey’s (2005) research on thrust faulting and groundwater potential in the Blue Ridge, to discern between hydrogeologically appealing thrust fault lineaments expressions and any other common lineament expression is impossible without some amount of research into substrata, which can quickly become expensive. The

power of lineaments comes into play when they are used selectively by experienced and professional hydrologists who integrate them into a project that uses other significant techniques such as borehole data and resistivity profiles to explain groundwater occurrence in complex terrain (Sander 2007).

When reviewing the literature of modern techniques in identifying high groundwater yields in fractured crystalline environments, undoubtedly lineaments will be a topic that is highly discussed. They certainly have their advantages and drawbacks, one being that they are frugally produced with technologies many earth science researchers already have access to. Sander (2007) discussed this point as a paradox, one side being the ease of researchers being able to locate the tools needed employ lineaments in hydrological studies. The other side being that ease of employing lineaments opens the door for lineament use by one who may not fully understand what they are doing. But just as the critics of the LeGrand (1967) model could comment on its generalities (Seaton and Burbey 2005) and subjectivity, the same has been applied to lineaments. Synthesis is a common topic in contemporary science, but is not always employed, many times giving way to schools of thought or the inertia of antiquated ideas. But it seems in this case there is something to be gained from both lineament analysis and from LeGrandian techniques. Both make sense conceptually, but have seen their share of criticisms when adhered to absolutely, and without expert interpretation and assessment.

## **Geomorphometric Analysis for the LeGrand (1967) Model**

### **Introduction: Defining Landforms**

A major drawback to the LeGrand (1967) model is the vagueness of the categories that users must discriminate between to rate a potential well site per the model's method. For some time, it has been recognized that many geographic phenomena lack precise definitions (Fisher and Wood 1998, Smith and Mark 2003, Deng 2007) but most people, from an earth scientist to a child could point to these objects, and other geographic phenomena and identify them easily. If one were to ask after the identification where those geographic entities end and begin, that would be tougher. More importantly, if two people had to compare their results, they would certainly be somewhat different, or they might have used differing terminology resulting in further semantic debates.

Unfortunately, this method fails in a scientific setting as well in everyday life. It may be easy to pick out the categories LeGrand (1967) has set forth, but there certainly would be variability on a user-by-user basis. When one reads through the explanation of the methods behind the LeGrand (1967) model, it is not hard to grasp what underlying concepts he believes to be important, these being topographic sags or lows that have the potential to accumulate water drainage and high amounts of overlying regolith to act as a sponge to absorb water and allow its infiltration into the aquifer. It is also easy enough to rate sites based on the criteria set forth when analyzing topographic maps for landform categorization per the model. The problem lies in scientifically replicating the LeGrand method.



Implementation of the LeGrand (1967) system in a GIS requires the computational derivation of geomorphic landforms from DEM derived coverages and the use of them in varying combinations (Irvin, Ventura, and Slater 1997; Burrough, Van Gaans, and MacMillan 2000; Hengl, Gruber, and Shrestha 2003, 3-4; Klingseisen, Metternicht, and Paulus 2008), the branch of science that analyzes and quantifies earth's surface and is referred to as geomorphometry (geomorphometry.org 2009). Contemporary literature from various disciplines shows the common goal of accurately representing landforms in a GIS, and commonly uses fuzzy set theory to assist in determining these landforms (Irvin, Ventura, and Slater 1997; Lagacherie et al. 1997; Roberts, Walker, and Dowling 1997; Burrough, Van Gaans, and MacMillan 2000; Hengl, Gruber, and Shrestha 2003; Hengl, Walvoort, and Brown 2004; Schmidt and Hewitt 2004). The revolutionary fuzzy set theory was first introduced by Zadeh (1965), in which the basic concepts of the theory were described. The idea revolves around differing classes of phenomena in the real world that do not have "precisely defined criteria for membership" (Zadeh 1965, 1). Instead, fuzzy sets hinge on the idea of a continuum of membership in a certain class; ranging from 0 being no membership and 1 being full membership (Hengl, Walvoort, and Brown 2004; spatial-analyst.net 2008). In the GIS raster scenario, each pixel is analyzed on the criteria set by the model and its membership to a certain class is designated somewhere on the continuum of 0 to 1. The resulting layer's pixels' memberships are ultimately determined by their "affinity" for a membership in comparison to the other membership classes (Burrough, Van Gaans, and MacMillan 2000). In this, the pixel's membership continuums are reduced from  $\{X_1, X_2, X_3, X_4, \dots\}$  number of classes to  $X_y$  in the final landform layer.

Fuzzy set theory is a useful tool in defining landforms but other methods have been used to delineate these phenomena as well. J. G. Speight of the Australian Division of Land Use Research is a highly referenced author who used field techniques and experience to give precise definitions of landforms and what justified the “sharp” (not fuzzy) boundaries between them. He used the idea of local relief and the scale at which these entities were considered to define the landscape, and frequently employed a quantified scale of slope steepness to further define the landforms in question (Speight 1990). These procedures were outlined for an in-field survey for a rather localized area. Speight acknowledged that procedures and outlines work well for land use planning and to be able to find the “relationships to support the extrapolation of point observations” (Speight 1990, 9).

Landforms are easy enough to discriminate from one another when we are on the landscape ourselves and field observations with a guide such as Speight’s (1990) work would aid in methodic classification, but to define them in a GIS requires a numerical description that human cognition does not translate to easily (Fisher and Wood 1998; Smith and Mark 2003). Even when we as the information system user look at a visualization of topography, we may easily see and concur with other users where a mountain or plain appears to be. This agreement does not justify a landform or geomorphic boundary to the information system unless parameters for that description are set forth. Thus ensues the quest to delineate boundaries we as the information system user can agree with, and that the information system can distinguish.

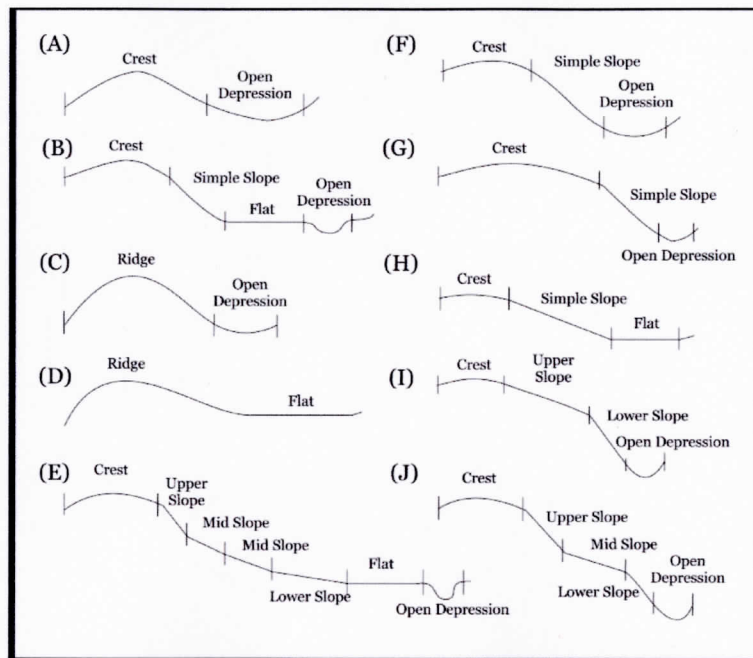


## *Background*

The LeGrand (1967) model was developed before the advent of GIS but continues to dominate basic groundwater modeling for the Blue Ridge and Piedmont of North Carolina (Heath 1980; LeGrand 2004; Seaton and Burbey 2005). Without the aid of universally applicable measurements for the LeGrand model, the topographic terms are familiar but nonetheless very vague for replicatable testing. In an attempt to get earth scientists on the same page with regard to what geographic phenomena are termed as in the real world, attempts have been made to assign systematic and quantifiable definitions to disambiguate varying vague definitions as in Figure 1 and many others. This issue was addressed at length by Fisher and Wood (1998) with an example of modeling these geographic entities in the GIS environment. The principle guide used for this thesis is Speight's (1990) Landform section of the Australian Soil and Land Survey Field Handbook on geomorphic units. This section gives common terminology for slope class breakpoints to indicate when generic slope classes begin and end (e.g. flat and gentle) as well as outlining upper, mid and lower slopes (Figures 4 & 5); this was quantified in the GIS environment for DEM data in later work by Giles and Franklin (1998, 257-259) (Klingseisen, Metternicht, and Paulus 2008). Speight also outlined what criteria should be present to justify basic landforms such as crests or ridges, and flats and plains (Speight 1990). These various numeric definitions with the aid of third-party geomorphometric software (Klingseisen, Metternicht, and Paulus 2008) referencing the same manual by Speight (1990) and the landmark work of Wilson and Gallant (2000) aid in defining what constitutes the topographic categories of the LeGrand (1967) model.

Crests	Area high in the landscape, having positive plan and/or profile curvature
Depression	Area low in the landscape, having negative plan and/or profile curvature, closed: local elevation minimum; open: extends at same or lower elevation
Flat	Areas having a slope $< 3\%$
Slope	Planar element with an average slope $> 1\%$ , subclassified by relative position
Simple slope	Adjacent below a crest or flat and adjacent above a flat or depression
Upper slope	Adjacent below a crest or flat but not adjacent above a flat or depression
Mid slope	Not adjacent below a crest or flat and not adjacent above a flat or depression
Lower slope	Not adjacent below a crest or flat but adjacent above a flat or depression

**Figure 4. From Klingseisen et al. 2008 (Speight 1990).**



**Figure 5. From Klingseisen et al 2008 (Speight 1990).**

Klingseisen, Metternicht, and Paulus (2008) published an article outlining the use of Speight's (1990) Landform text in the GeoMedia 5.2 environment via a software program called Landform 2 (Klingseisen 2004). The raster based program uses DEM data to delineate basic landforms in Geomedia 5.2's "Grid" extension.

To be able to quantify some of the vague terminology that Speight (1990) used, Klingseisen, Metternicht, and Paulus (2008) relied upon the work published

on quantifying topographic phenomena by Zevenbergen and Thorn (1987) that used map algebra to produce planar and profile curvature, which is a common reference and grid function for many GIS platforms (ArcMap 9.3). Landform 2 also uses less common map algebra functions developed by Wilson and Gallant (2000) to produce local relief and elevation percentile cell by cell in the raster matrix. Local relief is a common concept in earth sciences and is quantified by running a circular local scan window for maximum and minimum values and subtracting the two; the result is the local relief for the home location cell (Klingseisen, Metternicht, and Paulus 2008, 113). Elevation percentile is “a ranking of a point’s elevation relative to all other points in a circular scan window” (Klingseisen, Metternicht, and Paulus 2008, 113; Wilson and Gallant (2000). This is computed by choosing a scan window radius, and dividing the all cells within it lower than the home cell’s elevation, by the total number of cells within the radius; thus giving a percentile matching the Wilson and Gallant (2000) definition (Klingseisen, Metternicht, and Paulus 2008, 113).

Transitioning between GIS platforms was a common occurrence in this thesis work, due to strengths and weaknesses in differing software. Landform 2 was created for Intergraph’s Geomedia and Geomedia Grid 5.2 GIS environment. The geomorphometric processing was executed in Geomedia, requiring some conversions and calling for some dialogue on the idiosyncrasies between the ArcInfo 9.2-9.3 and Geomedia 5.2 environments that would benefit the reader if they wished to perform this analysis on their own study area.



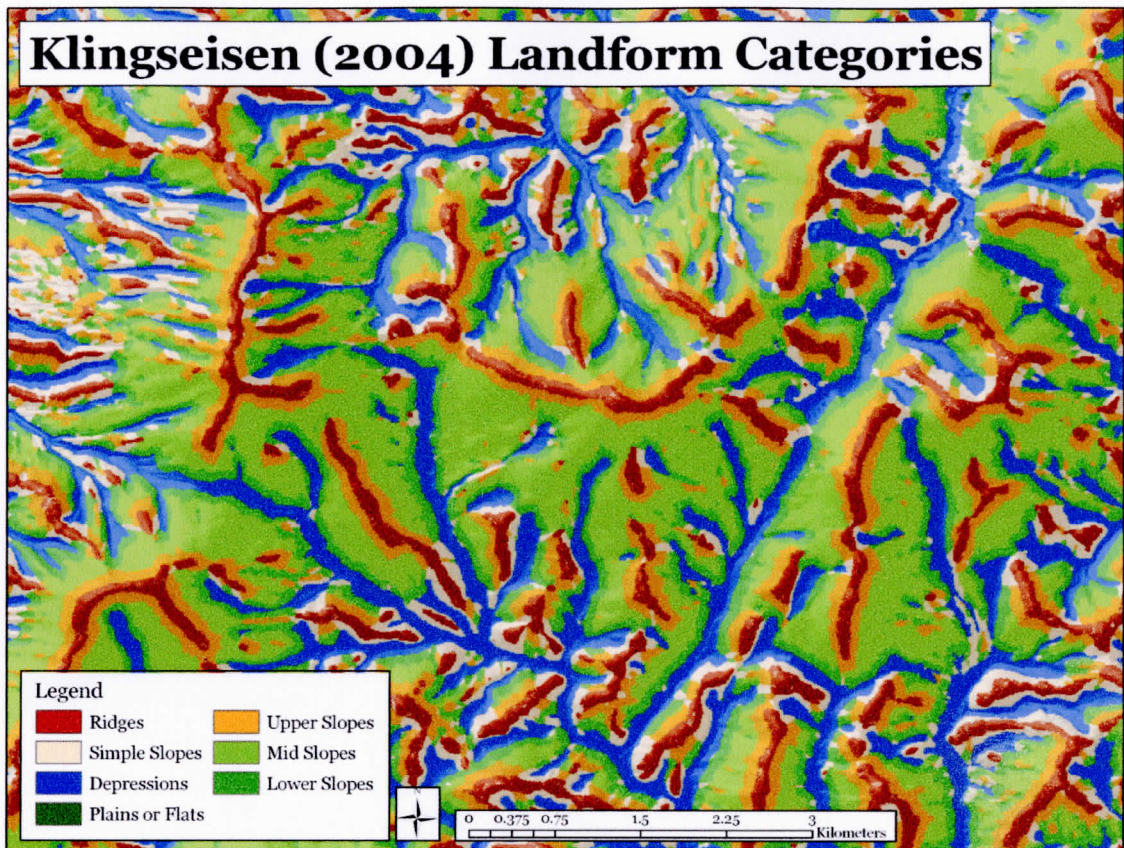
## *Methods*

Landform 2 requires the user to have Geomedia 5.2 and its Grid 5.2 extension up and running in a Windows environment. The Landform 2 manual is very self explanatory with regards to installing the third-party software and taking the user through the all the preprocessing steps. Geomedia 5.2 running the Landform 2 software works best when using 10 meter (or similar resolution) DEM images from the National Elevation Dataset (NED), this study found that these are best imported as “Floating Point” or .flt files. NED rasters are contiguous elevation data able to fully cover a study area, and are recommended because artifacts at mosaic points proved to be problematic when processing, by giving obvious erroneous outputs that ran along the edges of 1:24,000 DEM mosaic edges. Inside of the Geomedia workspace in which the raw DEM is located, the user must specify a “warehouse” in which the data structure format will be contained as well as resulting layers derived from queries, digitization, or raster processing. At this time the grid tab will become active and the user will be able to import file(s) via the study area option the recommended NED 10 meter DEM. The import window will require a .csf file or a coordinate system file (similar to .prj file in ESRI products). The best way to create this file is to click on the view tab in the Geomedia window and then access the GeoWorkspace Coordinate System option, where the user can select the projection, datum, and coordinate system of the incoming NED DEM. When the DEM is imported it now may be viewed via the Layers and View Layer(s) options, and processed in LANDFORM2.

Because the Landform 2 program is third-party add-on software, it offers limited support other than direct contact with the author. The author in this case was very responsive to questions and problems with the software. The first of these was a bug that did not allow the interface of Landform 2 to process for local relief; which is a base grid layer that Landform 2 uses for landform classification (Klingseisen, Metternicht, and Paulus 2008, 112). Correspondence with the author and interpretation of the algorithm outlined in Klingseisen, Metternicht, and Paulus (2008) for local relief allowed me to get around the program's bug and manually processing for local relief was achieved. This is a simple function that uses two DEM derived layers that are the result of a local circular scan window of 100 meters in diameter; the first being the maximum elevation value within that window and the second being the minimum. The maximum local elevation was then subtracted from the minimum local elevation to result in the local relief layer (Klingseisen, Metternicht, and Paulus 2008, 113, Bernhard Klingseisen, Curtin University of Technology, January 2008, email correspondence) (With the aid of the Wilson and Gallant (2000) text and knowledge of basic raster operations the user could run all of the DEM processing manually per the Klingseisen, Metternicht, and Paulus (2008) Landform 2 logic in many GIS platforms that have some type of raster program associated with them. This was not the case in this work, but an after note if a GIS technician did not have access to GeoMedia 5.2 and the Landform 2 software). After this the chronology of processing outlined in the article (Klingseisen, Metternicht, and Paulus 2008) and in the Landform 2 manual (Klingseisen 2004) could proceed. These categories Landform 2 processed for are not all that the LeGrand (1967) model implies, but they are most of the basic landforms that LeGrand references (Figure 6).

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**Figure 6. Landform 2 generated landform layer (Elk Knob State Park area).**

The terminology referring to the grade of the terrain in figure 1 is also common but vague. These terms (Table 1) used by LeGrand (1967, 2004) as defined by Speight (1990) are as follows:

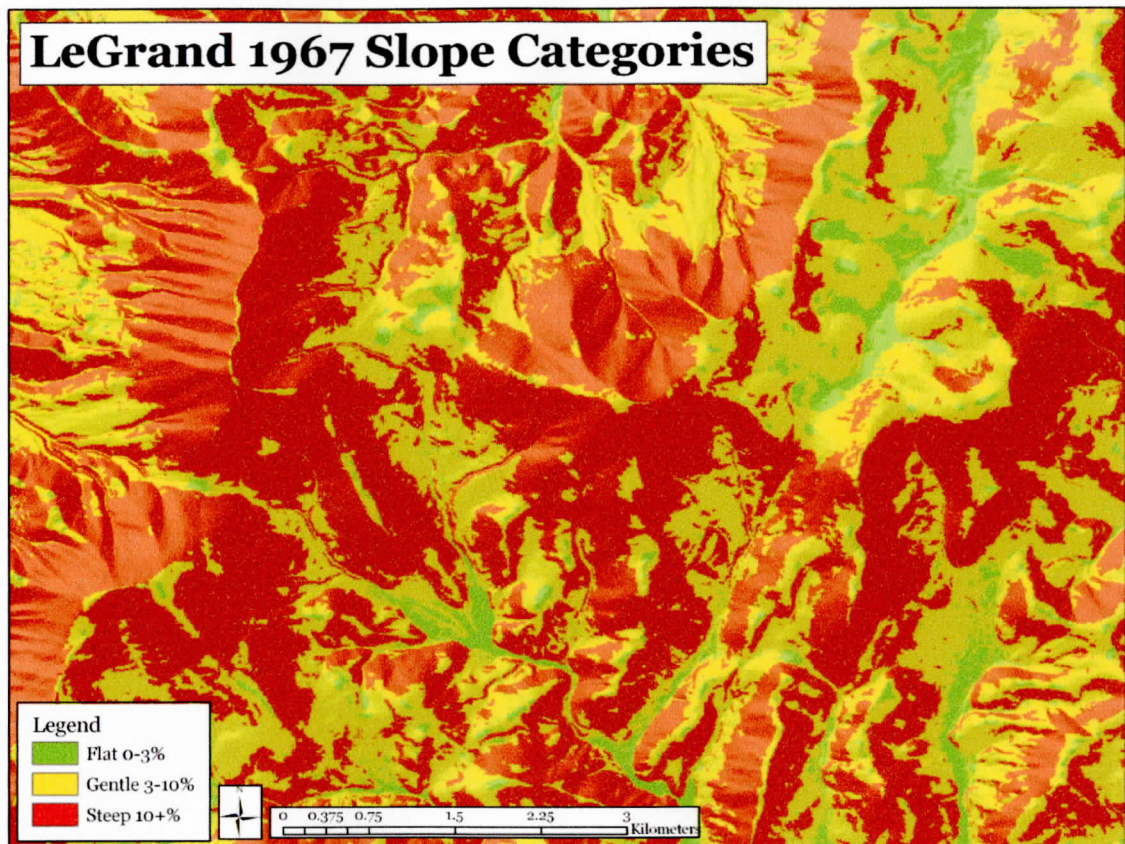
Flat	0-3% slope grade	Gentle	3-10% slope grade
Moderate	10-30% slope grade	Steep	30-60% slope grade
Precipitous	60-90% slope grade		

All of these slope classes were not used in LeGrand's (1967) model (Table 1) for describing how steep these morphological units were in the Piedmont and Blue Ridge; flat, gentle, and steep were the only terms used. So, there was a considerable gap between the categories of gentle and steep that LeGrand (1967) did not refer to;



LeGrand's slope categories are seen in Figure 7, which was used to build the raster model. Percent slope is an easily calculated layer in a GIS, and to fit this into a functioning LeGrand (1967) model, it was reclassified as such:

Flat Slopes	0-3%
Gentle Slopes	3.-10%
Steep Slopes	10% +



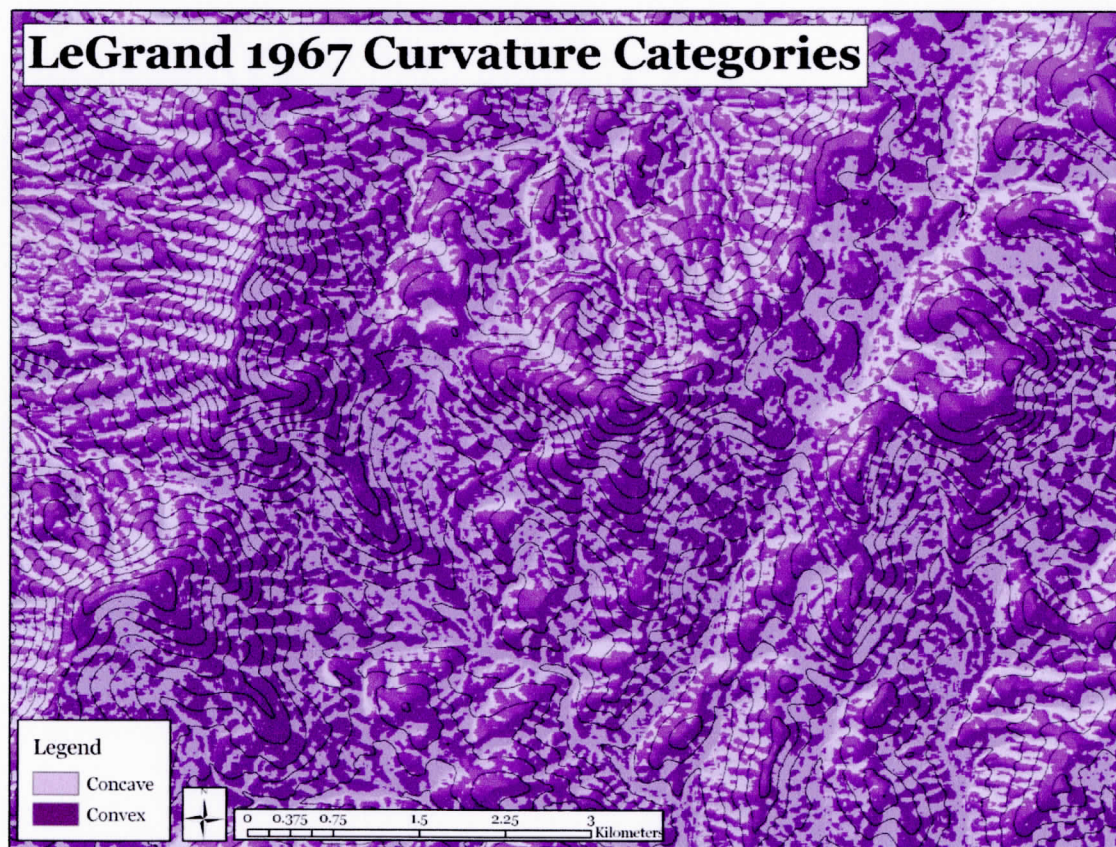
**Figure 7. Reclassified Slope Layer per LeGrand (1967) slope descriptions (Elk Knob State Park area).**

It is debatable why the slope classes in LeGrand's (1967) model jump from gentle to steep, with no intermediate. Perhaps the topographic categories that did not use a slope description (e.g., "valley bottom" as opposed to "flat valley bottom") accounted for slope gradient in their very definition. That is to say that if one could identify what landform LeGrand (1967) was referring to that did not use any type



additional slope description, then the further elaboration may be redundant. An example could be the category “midpoint ridge slope” which has no “flat”, “gentle”, or “steep” gradient description. If this was interpreted as a mid slope region, then slope gradients would generally be intermediate when compared to the grades of the lower and upper slopes. Another side may be that there was no intermediate slope category and LeGrand’s slope classes did indeed transition from gentle to steep. Without additional information from LeGrand himself, these ideas are conjecture but important ideas to consider when modeling such a popular concept.

Figure 8 shows the raster interpretation of LeGrand’s (1967) terms such as “rounded” and “draw”. These terms are describing the terrain’s natural tendency to shed or accumulate water. The combined profile and planar curvature layer processing found in many GIS platforms is a good description of how convex or

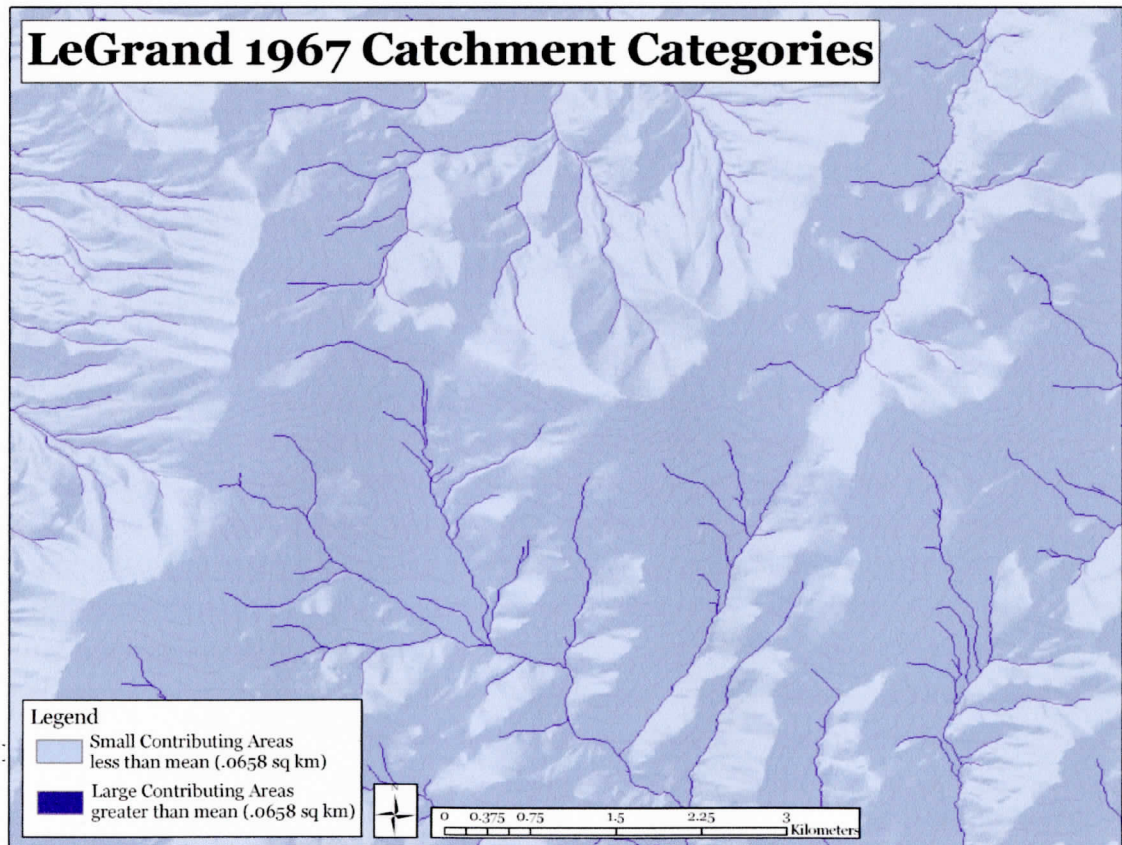


**Figure 8. Reclassified and Generalized Curvature Layer (Elk Knob State Park area).**



concave the landscape is. The terminology of the model is very general and hints at general topographic trends, for this reason the curvature layer was reclassified as: negative curvature area being concave and positive curvature areas being convex. After reclassification, a 5x5 majority filter was scanned across the new curvature layer to smooth out noise and be able to see the general convexities and concavities that LeGrand (1967) seemed to be referring to.

LeGrand (1967) also mentioned (Table 1) the size of the catchment that the draw sits in, that being either narrow or large. It is not clear whether the intent was the actual basin that the well sat in, bringing in the geographic issue of scale, or the contributing area above the point. For this model, the method considered the contributing area above the point in question (Figure 9). This was achieved by



**Figure 9. Catchment Categories per the LeGrand (1967) model (ArcMap 9.3) (Elk Knob State Park area).**



calculating the flow accumulation (ArcMap 9.3) for the study area and examining its statistics. The mean of the flow accumulation model was .0658 square kilometers. That can be interpreted as, on average .0658 square kilometers contribute to any given point in the study area. Since LeGrand (1967) made no reference as to the scale or the amount of land “narrow” or “large” meant, this seemed to be valid compromise. The issue of geographic scale is very important in this scenario. The mean would certainly differ if the area in question was at the sub-basin to primary-basin scale, rather than the non-hydrologic unit of the county wide scale. If the model implementer was to literally interpret the descriptions, they might come to the conclusion that LeGrand (1967) was referring to the actual drainage basin size and/or shape, and since drainage basins are nested by nature, it would be difficult to logically determine the hydrologic significance of well site that could be in the largest basin in the study extent, but on or near a ridgeline. It is also problematic that the terms “narrow” and “large” are used since they are describing different characteristics of drainage basins. The opposite to narrow would seemingly be something like wide, and of “large” would seem to be small. One can only guess what LeGrand (1967) was referring to, but it was seen as a safe guess that “catchment area” was referring to the hydrologic contributing area above the point in question, and not the size or shape of the catchment the point happen to be sitting in.

### *Model Implementation*

After processing for many different aspects of geomorphic units in the study area, it was possible to begin combining these different descriptions of the terrain to suit the LeGrand (1967) model. The base layer for the LeGrand (1967) GIS

environment was the Landform grid from (Klingseisen, Metternicht, and Paulus 2008). With these general landforms delineated the additional descriptions LeGrand (1967) used can be added in with the base geomorphic units to suit the model, these being the three terrain descriptors above. The raster logic of the model was created by reclassifying the unique values of each geomorphic attribute layer as:

<u>Landforms</u>		<u>Slope</u>		<u>Curvature</u>		<u>Catchment</u>	
Ridges	1000	Flat	100	Convex	10	Small	1
Simple slopes	2000	Gentle	200	Concave	20	Large	2
Depressions	3000	Steep	300				
Plains	4000						
Upper slopes	5000						
Mid slopes	6000						
Lower slopes	7000						

**Table 3. Model Reclassification Logic using Landform 2 (Klingseisen, Metternicht, and Paulus (2008), Speight (1990), and Zevenbergen and Thorn (1987) logics in combination with a flow accumulation raster.**

These four raster layers were then summed in the raster calculator for new unique values in each pixel cell. This left a substantial amount of overlap between some categories of landforms per LeGrand (1967). For instance, the “Mid Slope” group had values shown in table 4.

These are essentially where all of these layers overlapped each other, so what do we call these combinations in the LeGrandian logic? If the model just went by the actual words of LeGrand’s model, then some categories would be vastly under-represented or over-represented, so subjective decisions as to what to aggregate into LeGrand’s topographic categories must be made with regard to the logic of the model. If we considered the “ridges” category combination, the idea that ridges are

Model #	Landform	Slope	Curvature	Catchment	Percent of Pixels in Raster Model
6111	Mid Slope	Flat	Convex	Small	0.0805%
6112	Mid Slope	Flat	Convex	Large	0.0013%
6121	Mid Slope	Flat	Concave	Small	0.0905%
6122	Mid Slope	Flat	Concave	Large	0.0005%
6211	Mid Slope	Gentle	Convex	Small	1.0947%
6212	Mid Slope	Gentle	Convex	Large	0.0085%
6221	Mid Slope	Gentle	Concave	Small	1.5570%
6222	Mid Slope	Gentle	Concave	Large	0.0041%
6311	Mid Slope	Steep	Convex	Small	2.5660%
6312	Mid Slope	Steep	Convex	Large	0.0012%
6321	Mid Slope	Steep	Concave	Small	2.9794%
6322	Mid Slope	Steep	Concave	Large	0.0003%

**Table 4. Mid Slope Group from Raster Model logic, taken from appendix A.**

low for groundwater potential is based on the idea that these areas of high relief are above the landscape because of their strength in resisting weathering and erosion, so they are less likely to have joints and fractures that may house groundwater.

However, what LeGrand (1967) was concerned with is the layer of regolith above the bedrock interface and the general absence of fractures in topographic highs. In the LeGrandian concept, most of the water storage was in the saturated regolith layer, specifically in the transition zone where residuum and saprolite may be found (LeGrand 2004). So the ridges also have a low number on LeGrand's (1967) scale because of low amounts of overlying material and resistance to weathering making for less of a chance for fractures. When applying this concept to the model's unique value combinations (Appendix B), there are areas that are categorized as ridges that contain some amount of concavity and flat to gentle slopes but it would



not be prudent to classify these upland concavities as draws, even though draws are parts of slopes. There may also be overlap where ridges end and slopes and parts of slopes end and begin. The discussion of interpreting the catchment category above also results in large differences in the raster model (Appendices A & B). By changing the interpretation of large and narrow catchment areas the ridge categories raster combinations are eliminated completely. In appendix A, the large and small catchments were divided by the mean area of the basins assembled from the National Hydrography Dataset (NHD). This is a representation of the discussion following figure 9, in which the model implementer interprets the catchment categories to be the actual area of the drainage basin in which the well in question sits. In this case, there is a full representation of every possible combination of the raster logic. The raster model that assumes flow accumulation for the catchment categories does not have any combinations of planar ridge areas that also have some amount of concavity and a large contributing area, or in other words ridge areas did not coincide with any high contributing area values (Table 5; Appendices A & B).

In this case and several others it is impossible to say what exactly LeGrand (1967) meant by his topographic categories, even with modern landform and landscape quantification. So interpreting LeGrand's (1967, 2004) categories is inherently subjective but given the reproducibility of these methods that rely on LeGrandian logic, these efforts move towards an unbiased and fair representation of what LeGrand (1967) may have had in mind.

<b><i>Catchment Category - NHD logic</i></b>		<b><i>Catchment Category - Flow Accumulation Logic</i></b>	
Value	Number of Pixels	Value	Percent of Pixels
1111	0.04995%	1111	0.06233%
1112	0.01618%	<i>nodata</i>	
1121	0.86011%	1121	1.20985%
1122	0.36992%	1122	0.00002%
1211	0.32615%	1211	0.42560%
1212	0.13754%	<i>nodata</i>	
1221	5.60292%	1221	8.17541%
1222	2.79390%	1222	0.00001%
1311	0.54780%	1311	0.78203%
1312	0.23649%	<i>nodata</i>	
1321	5.62577%	1321	8.39724%
1322	2.79258%	1322	0.00001%

**Table 5. Raster model differences between catchment category logic.**

### *Geomorphometric Results and Discussion*

Appendix A shows a brief explanation for the logic of why each unique value was classified as it was in ArcMap, with possible arguments for inclusion into another category. The logic of the model for the LeGrand (1967) groundwater model (Appendix B) gave varied results, but appeared to be a fair representation of what LeGrand (1967) had in mind when naming the topographic categories (Appendix B; Table 1); but generally can be debated on the basis of semantics. The raster model also has two additional categories to that of LeGrand's (1967) original model; these

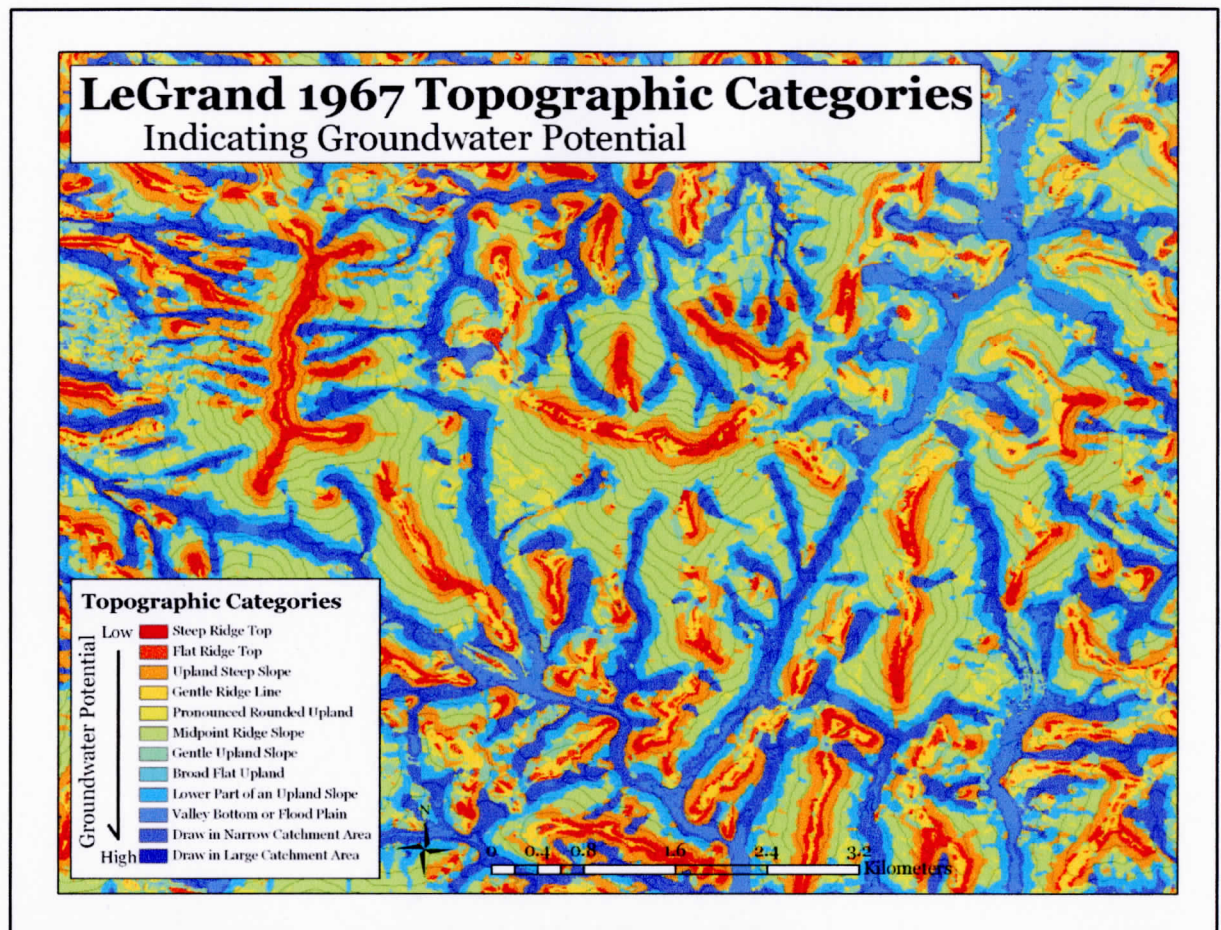
are Flat Ridge Tops and Gentle Ridge Lines. The two new categories have been assigned topographic points of 1 and 3, respectfully. This is an example of the model criteria being in agreement in the raster logic and with semantics, but failing basic hydrogeologic truths in these settings. The new categories were created out of a need to better represent the hydrologic significance of ridge areas in the model.

Ridges commonly have flat to gently sloping areas (in this case 0-10%) as they are the crest of slope (Speight 1990). If these categories were not created, these areas would be classified as “gentle upland slopes” or perhaps “broad flat uplands” with topographic points of 7 and 8, respectfully. Though ridgelines are associated with these slope gradients and this is an accurate representation of landform elements further dissected by slope, one cannot assume that out of a possible 18 points modeling groundwater potential, LeGrand (1967) put these ridge areas with flat to gentle inclined slopes, somewhere in the middle (Figure 10).

The simple slope landform elements present an interesting representation of the LeGrand (1967) model too. These simple slope areas are slopes that did not have adequate morphological development following Giles and Franklin (1998) work on where significant changes in slope along a slope’s profile deemed the dissection of upper, mid, and lower portions appropriate (Klingseisen, Metternicht, and Paulus 2008, 114-115). In the raster model’s logic these simple slope areas that also coincided with steep (10+ %) gradients scored very low on LeGrand’s (1967) chart (Table 1 & Appendix B). This is to say that if this model was taken as an accurate representation of LeGrand’s (1967) topographic categories that most slopes without



significant slope changes along their profile would be considered unfavorable due to the high amount of area that was classified as steep (56.7% of area analyzed).



**Figure 10. Raster Model of LeGrand (1967) Topographic Categories.**

There could be many more issues with the classifications, such as the logic of the catchment categories discussed previously. Using the NHD catchment polygons for the extent of Watauga County could be argued as valid, given the depth of explanation by LeGrand (1967), but does not make sense hydrologically. Whether or not a well's position happens to be in a large drainage basin doesn't speak to how much water has the potential to recharge the area surrounding it. So this interpretation was a strict and, in my opinion, erroneous way to interpret a logical

point that LeGrand (1967) included in his report, but did not precisely define. It makes more sense to use flow accumulation area above the well.

It was for these reasons that the model logic in Figure 9 was created that would suit the troublesome “ridges” category better as well as the “catchment” category. The “ridges” categories problems were solved by adding two additional categories that were not in the original LeGrand (1967) scheme, but the point scheme that LeGrand uses leaves room for (Figure 1). Given how the point scheme in LeGrand’s (1967) topographic category scales from 0 to 18 with only 10 categories, and that LeGrand (1967) leaves up to 5 points of different user interpretation, the categories of “Flat Ridge Top” and “Gentle Ridge Line” should be an improvement in the topographic classification (Appendix B). The language for the catchment category was unchanged, but in model logic the catchments were defined by contributing area above the pixel the well fell in. By defining catchment category through a point’s contributing area (smaller or larger than the mean), the amount of land surface contributing a well could be known and compared with others to be able to group the wells into large and small catchment areas.

### *Geomorphometric Analysis Conclusions*

Interpretation of the LeGrand (1967) groundwater model for the raster environment inherently comes with a degree of uncertainty and subjective interpretation, but is greatly aided by the extensive amount of research in the geomorphometry field that has sought to clear up some of these common but elusive terms that LeGrand (1967) and many others use. The general model’s concept has dominated in explaining the occurrence of groundwater in the region, but despite



recent updates (LeGrand 2004) and further citations (Heath 1980), its terminology has been left the same since its publication in 1967. This work has sought to interpret the LeGrand (1967) terminology as accurately, unbiased, and with as much literary backing as possible. Though the interpretation is inherently subjective, the final classification of the topographic categories has considered and analyzed much more than originally was set forth in LeGrand's (1967) report. The subjective nature of interpreting the popular LeGrand (1967) groundwater model leaves room for further research into what variables explain the largest amount of variation in well yields. This is the next logical step in the pursuit of a greater understanding of this complex groundwater system, whether the categories are taken directly from LeGrand's (1967) work or not.



## **The Watauga Study Area and Lineament Procedures**

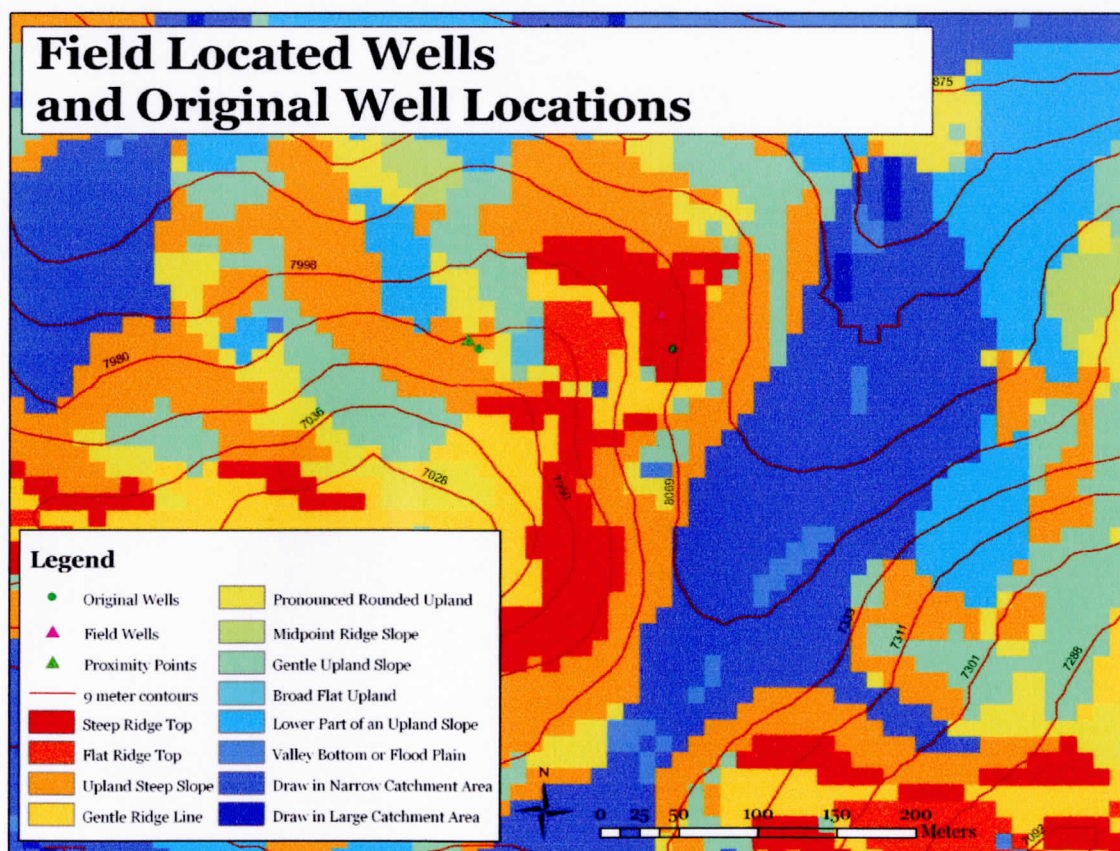
### *Introduction – The Watauga Wells Database*

To analyze how well the LeGrand (1967) model predicted well yields, actual wells with yield were needed. The well database used in this study was generously provided by the local United States Geologic Survey (USGS) office in Arden, North Carolina. The original database contained 667 wells in Watauga County, North Carolina. One well point was thrown out due to obvious erroneous coordinates locating it several hundred miles away from the county. Any wells without yield data were discarded as well, making the final count 628 wells. Each well had attribute data that were used in analysis including: coordinates, casing depth, and yield. In this study and others (Daniel 1989, Knopman and Hollyday 1993; Neves and Morales 2007, Brad Huffman, US Geological Survey, October 2007, Phone Interview) the casing depth of the well was used to estimate regolith thickness. This eliminated the estimations that would be used when assessing a potential well site's regolith thickness in the field.

### *Field Methods*

In order to get an idea of the accuracy of the coordinate data for the wells, a subset of the wells was found and their coordinates taken with a Trimble GeoXT Global Positioning System (GPS) unit. Over a period of two days in late December 2008, 12 randomly generated well sites were located to either collect a GPS point on the actual borehole covering or collect a proximity point near the well in question. Proximity points were used as a last resort measure in the instance that a well covering was inaccessible; this included not being able to contact the well owner, or if

the well itself was unable to be located. In the instance of taking a proximity point the borehole cover or the well house was photographed with a reference as to where the GPS proximity point was taken. There was only one case of a well that could not be located, so a proximity point was taken directly where the GPS referenced and a picture of the area was taken. On average the GPS points on the well coverings were 52 meters away from the original coordinate data. When the output of the LeGrand raster model was used as a backdrop the well points and proximity points were no more than 5 topographic points from the original well point (Figure 11). Since the accuracy of the well coordinates did not substantially affect the model categorization of the well point, the original coordinate data were used with the assumption that the coordinate data's accuracy was suitable for this study (Huffman et al. 2008).



**Figure 11. Actual well locations with original coordinate data.**

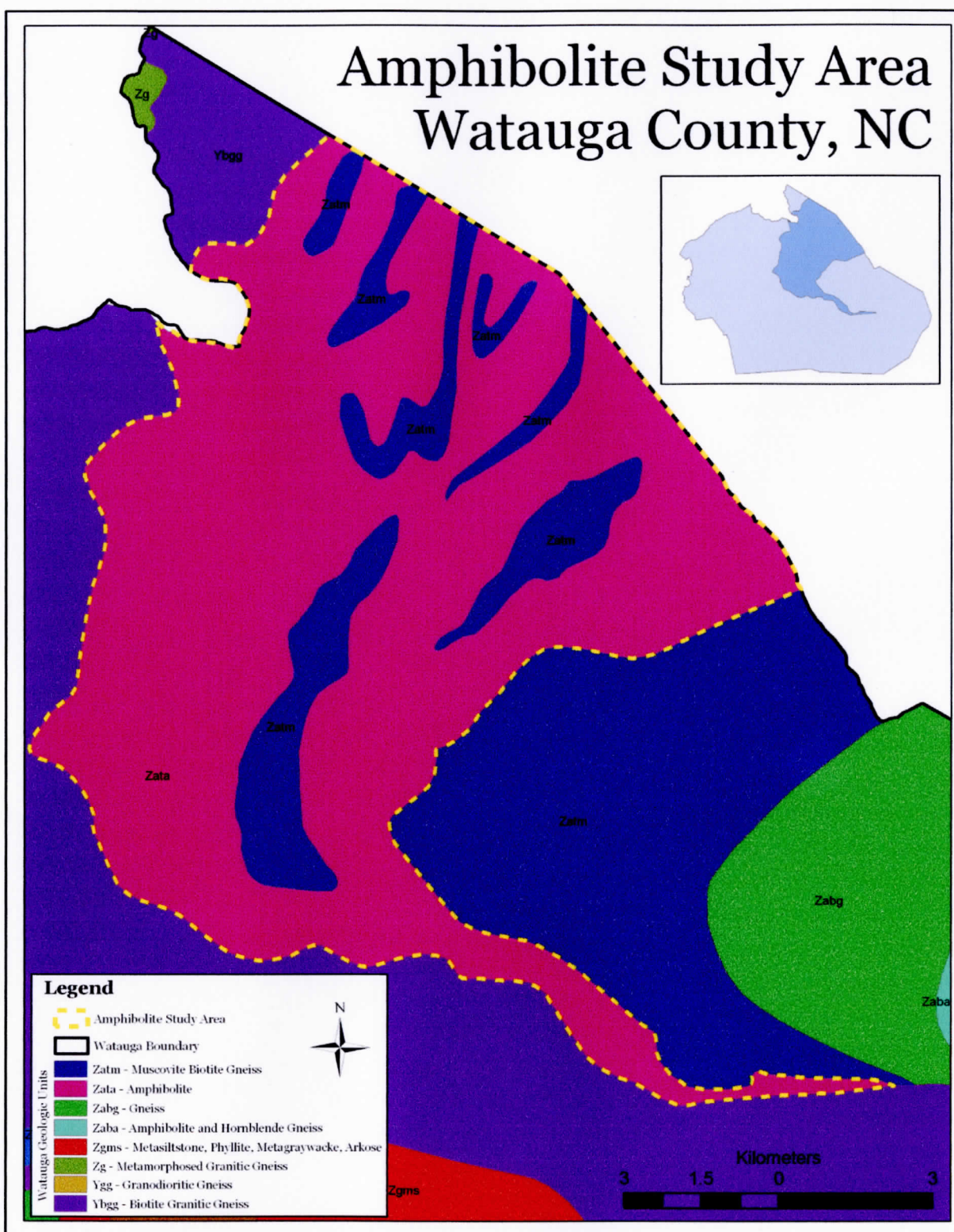


### *Lineament Procedures and Methods*

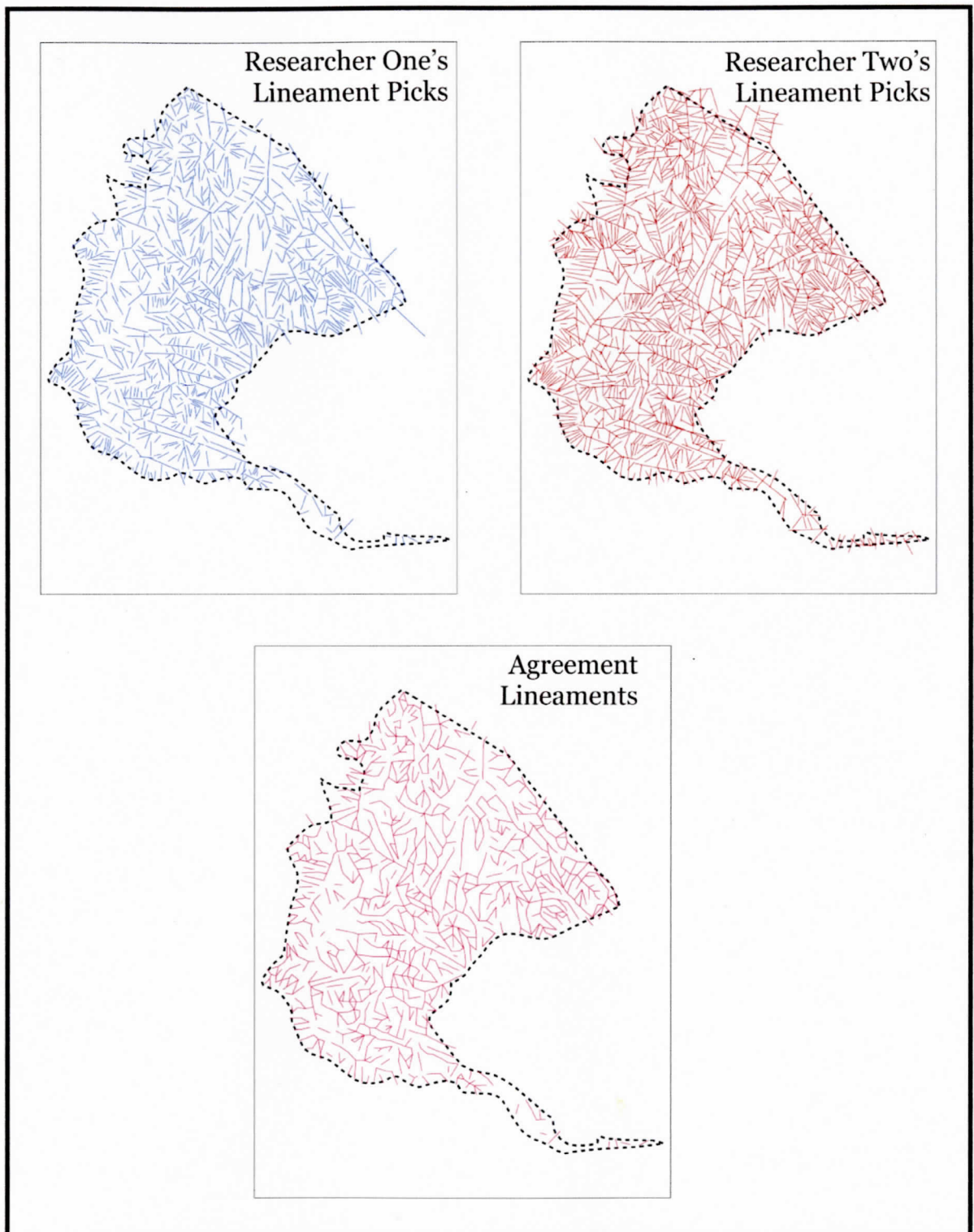
Lineaments were digitized in ArcInfo 9.3 by two different researchers to investigate their relationship to well yield. The two researchers were Dr. William Anderson and Williams Gandy. Each user did so using 20-meter contour data at the 1: 24,000 and 1: 48,000 scale. To stay consistent with topographic trends that are probable in a single lithology, the area that was used for lineament analysis was confined to the amphibolite region of Watauga County, North Carolina. This region, however does have small areas of a gneissic lithology, which were treated as the same study area (Figure 12). Each researcher's 1: 24,000 and 1: 48,000 scale lineament picks were combined with the merge function via ArcToolbox's data management tools. This produced a single polyline file that represented each researcher's digitized lineament picks at both 1: 24,000 and 1: 48,000 scales.

Undoubtedly, the lineaments between researchers would not directly coincide. For this reason ArcToolbox's intersect command was used to combine only the lineaments that were referencing the same topographical feature within a given fuzzy distance of 75 meters in any direction. In the tool's dialogue the XY tolerance was set to 75 meters to account for discrete differences between researchers digitizing. This would allow for the intersection of polylines within 75 meters that were representing the same lineament. The result is a lineament map that is more conservative than that of most of the initial digitizing by a single researcher (Figure 13). The final data product was a combined effort of the researchers' decisions as to where lineaments exist, essentially only expressing areas where both researchers found significant evidence of a lineament.





**Figure 22. Amphibolite study area for lineament analysis.**



**Figure 13. Lineament map progression, each researcher's lineament map is a combination of picks at both scales; the final agreement lineament map was used in analysis.**



### Using ArcView Avenue Scripts to Aid in Lineament Analysis

Kim, Lee, and Lee (2004) described the scripts they developed to optimize and analyze lineaments digitized by researchers in the GIS environment. The first two scripts, “Remove-Node” and “Generalize”, were part of the optimization processing for the lineament shape file; in a sense these were preprocessing commands that cleaned up the file. Kim, Lee, and Lee (2004, 1119) described the “Remove-node” script’s purpose as one that “reduces the nodes of lineaments”. This operation removes potential mistakes by the researchers digitizing and/or lineaments that may have been digitized more than once. The next command that Kim, Lee, and Lee (2004) described is the “Generalize” script. “Generalize” takes the angle of two intersecting lineaments into consideration, and decides whether to combine the two lineaments into one contiguous lineament or break them into two different lineaments. The angle that is to be the threshold is input by the user, and anything found smaller than the degree swath which was input is considered one lineament and anything larger is considered to be two lineaments (Figure 14). The

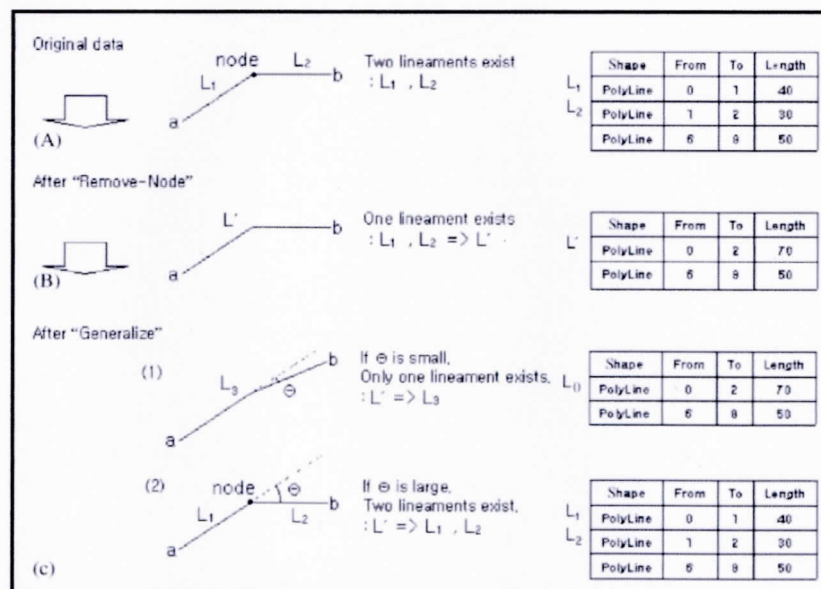


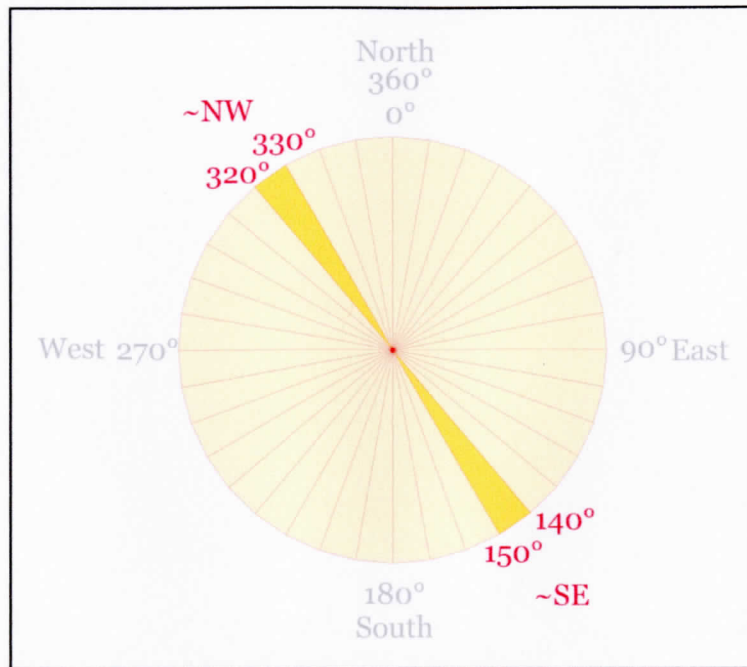
Figure 14. Source Kim, Lee, and Lee (2004).



default angle of the script is  $10^\circ$ , and by examining the lineament file after the “Generalize” script processed it at  $5^\circ$ ,  $10^\circ$ , and  $20^\circ$  the default of  $10^\circ$  was chosen for the amphibolite study area. No significant differences were seen in the alternative angle lineament files. With the agreement lineament map produced and preprocessing measures with the Kim, Lee, and Lee (2004) scripts taken, procedures with ArcInfo then allowed the randomly selected well file to “absorb” various attributes of their relationship to the lineaments in the amphibolite region.

The “L-Stat” script is the first script in the lineament analysis roster Kim, Lee, and Lee (2004) developed. This function gives basic statistics on the lineament file in the .dbf format for the user to integrate into their own analysis. The resulting .dbf table gives the overall length total for all the lineaments in the file, as well as the sum number of all the individual lineaments. The table also includes the sum number of individual lineaments and total length for specified azimuths as well. Before running the script, the user is prompted to input the range of angles that will define each azimuth category. That is, if the user accepted the default of  $10^\circ$  then the resulting output table would have its first azimuth category of  $270^\circ$  to  $280^\circ$ , ending at  $80^\circ$  to  $90^\circ$  (Figure 15). The table only defines azimuths in the top  $180^\circ$  of possible azimuths because the opposite degree swath that is represented is implied (i.e.,  $270^\circ$  to  $280^\circ$  would also represent  $90^\circ$  to  $100^\circ$ ).

If the user was interested at this point in lineaments in only a selected number of azimuths, then the “L-selection” tool can be used for extracting these lineaments that fit the designated azimuth criterion. This is a useful tool to further investigate lineaments found in geologically significant areas.



**Figure 15. Kim, Lee, and Lee 2004 logic for implied coincident lineament azimuth.**

Kim, Lee, and Lee (2004) also developed scripts that would append information to a well database in the form of a point file; the two scripts that were used in this study were “Dist-to-line” and “Dist-to-crosspoint” functions. The “Dist-to-line” script allows the user to select the well point file and then the lineament file to be analyzed in conjunction with another. The result is an update of the well databases attribute table, with a new category termed “Distance2Line” that displays the distance to the nearest lineament for each well point. The “Dist-to-crosspoint” script is used to append the distance of a well to the nearest lineament intersection. This process also produces a point file that shows all lineament intersections. The new category in the wells database is termed “Dist2CrossPt”.

The density of lineaments was another avenue of examination. Since this concept would generally represent a swath of area, the density of lineaments was calculated in the raster format with the aid of the spatial analyst tools in ArcToolbox.







hypothesis is that the data are normally distributed; only the data variables of LeGrand points and curvature were normally distributed in this case. For this reason, Kendall's non-parametric test was used to examine correlations between yield and the remaining variables to assess which variables were significantly correlated to use in a linear regression model. Kendall's correlation test revealed that well depth, casing depth, LeGrand points, and slope were all significantly correlated at least at the 95% confidence level (Table 6). These variables were selected for

Correlations									
			yield	welldepth	casingdepth	legrand_pn	cont_area	act_curv	slope
Kendall's tau_b	yield	Correlation Coefficient	1.000	-.483**	.310*	.295*	-.063	-.047	-.338**
		Sig. (2-tailed)	.	.000	.015	.021	.639	.709	.007
		N	32	32	32	32	32	32	32
	welldepth	Correlation Coefficient	-.483**	1.000	-.051	-.374**	.025	.135	.343**
		Sig. (2-tailed)	.000	.	.695	.004	.853	.289	.007
		N	32	32	32	32	32	32	32
	casingdepth	Correlation Coefficient	.310*	-.051	1.000	.369**	-.149	.238	-.119
		Sig. (2-tailed)	.015	.695	.	.004	.268	.059	.346
		N	32	32	32	32	32	32	32
	legrand_pn	Correlation Coefficient	.295*	-.374**	.369**	1.000	-.236	.037	-.408**
		Sig. (2-tailed)	.021	.004	.004	.	.081	.770	.001
		N	32	32	32	32	32	32	32
	cont_area	Correlation Coefficient	-.063	.025	-.149	-.236	1.000	-.255	.322*
		Sig. (2-tailed)	.639	.853	.268	.081	.	.054	.015
		N	32	32	32	32	32	32	32
	act_curv	Correlation Coefficient	-.047	.135	.238	.037	-.255	1.000	-.081
		Sig. (2-tailed)	.709	.289	.059	.770	.054	.	.517
		N	32	32	32	32	32	32	32
	slope	Correlation Coefficient	-.338**	.343**	-.119	-.408**	.322*	-.081	1.000
		Sig. (2-tailed)	.007	.007	.346	.001	.015	.517	.
		N	32	32	32	32	32	32	32

\*\* Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed).

**Table 6. Correlations for random33 Watauga wells.**

regression analysis and were then assessed for candidacy for a linear regression analysis.

The curve estimation function in SPSS allows the user to assess if a linear relationship is present between two variables; linearity between the dependent and independent variables is a requirement of a linear regression model (Moore 1999). Statistically significant linear relationships were only found between well yield and

well depth. For this reason, the yield variable was transformed by adding 10 to the sample to be able to take its log<sub>10</sub>. Adding 10 to each of well yield datum was necessary to be able to take the log<sub>10</sub>, due to 3 occurrences of completely dry boreholes resulting in a yield value of 0. This procedure normalized the data and significant linear relationships were observed between log<sub>10</sub>+10 yield (yield\_trans) and well depth (this time at higher significance), casing depth, LeGrand points, and slope (Table 7). With these linear relationships now in place a linear regression analysis was carried out via the linear regression function in SPSS. The Durbin-

Model Summary and Parameter Estimates							
Dependent Variable: log10+10 yield							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.434	23.044	1	30	.000	1.419	-.001
Logarithmic	.433	22.885	1	30	.000	4.115	-.553
Inverse	.378	18.233	1	30	.000	.335	163.838
The independent variable is welldepth.							
Dependent Variable: log10+10 yield							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.143	5.001	1	30	.033	.600	.005
Logarithmic <sup>a</sup>	.	.	.	.	.	.000	.000
Inverse <sup>b</sup>	.	.	.	.	.	.000	.000
The independent variable is casinodepth.							
Dependent Variable: log10+10 yield							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.122	4.182	1	30	.050	.423	.022
Logarithmic	.101	3.382	1	30	.076	.155	.242
Inverse	.084	2.765	1	30	.107	.953	-1.482
The independent variable is legrand pn.							
Dependent Variable: log10+10 yield							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.195	7.272	1	30	.011	1.175	-.028
Logarithmic	.171	6.170	1	30	.019	1.478	-.277
Inverse	.080	2.626	1	30	.116	.685	1.207
The independent variable is slope.							

**Table 7. Curve Estimations for Independent Variables in random 33 Watauga Wells.**



Watson statistic again confirmed randomness and thus only very weak positive spatial-autocorrelation with a value of 2.016 (Studenmund 1992, 343). The collinearity statistics did not find severe multicollinearity for any of the coefficients in the model, with variance inflation factor values all under 5 (Studenmund 1992, 411).

#### *Watauga County Linear Regression Results*

The four variables together explained 55 % of the variation in yield\_trans across Watauga County, with only the well depth and casing depth being significant at the 95 % confidence level (Table 8). At this point, the insignificant variables were thrown out to improve the model, leaving only well depth and casing depth to explain the variance of the yield\_trans. The two variables combined explained 51.7 % of the variation in the yield\_trans in Watauga County at a 99 % confidence level (Table 9).

The regression model shows a strong relationship between low well depths and the yield\_trans. These results of low well depths explaining higher well yields are converse to the Seaton and Burbey (2005) findings. Though Seaton and Burbey's (2005) research did not involve a population of wells that would account for wells shallower than 300 feet (91.44 meters) they were able to find high yields at higher depths than is usually assumed and were not totally arguing against the conceptual groundwater model for the Blue Ridge, but rather that it was too general and their

**Variables Entered/Removed<sup>a</sup>**

Model	Variables Entered	Variables Removed	Method
1	slope, casingdepth, wellddepth, legrand_pn	.	Enter

a. All requested variables entered.

b. Dependent Variable: log10+10 yield

**Model Summary<sup>b</sup>**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.742 <sup>a</sup>	.550	.483	.32843	2.016

a. Predictors: (Constant), slope, casingdepth, wellddepth, legrand\_pn

b. Dependent Variable: log10+10 yield

**ANOVA<sup>b</sup>**

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.557	4	.889	8.245	.000 <sup>a</sup>
	Residual	2.912	27	.108		
	Total	6.470	31			

a. Predictors: (Constant), slope, casingdepth, wellddepth, legrand\_pn

b. Dependent Variable: log10+10 yield

**Coefficients<sup>a</sup>**

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.526	.301		5.067	.000		
	wellddepth	-.001	.000	-.604	-3.984	.000	.726	1.378
	casingdepth	.004	.002	.330	2.257	.032	.779	1.284
	legrand_pn	-.011	.011	-.178	-1.033	.311	.565	1.770
	slope	-.013	.010	-.202	-1.323	.197	.717	1.395

a. Dependent Variable: log10+10 yield

**Table 8. Preliminary test and regression model for random 33 Watauga wells.****Model Summary<sup>b</sup>**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.717 <sup>a</sup>	.514	.480	.32939	1.979

a. Predictors: (Constant), casingdepth, wellddepth

b. Dependent Variable: log10+10 yield

**ANOVA<sup>b</sup>**

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.323	2	1.662	15.315	.000 <sup>a</sup>
	Residual	3.146	29	.108		
	Total	6.470	31			

a. Predictors: (Constant), casingdepth, wellddepth

b. Dependent Variable: log10+10 yield

**Table 9. Random 33 Watauga wells regression model 2.**

research proved that. Though the entire study area for this work is located in the Blue Ridge Province where thrust faulting is likely to occur, and thus potentially higher well yields at greater depths, the model found the opposite to be true. Daniel (1989, A26) discussed his work with the same idea and concludes that “very few wells have been drilled deep enough to test the full potential of the sites”. A histogram of the well depths for the random subset show that the mean well depth is about 430 feet (131.06 meters) (Figure 17). The graph of well depth to the yield shows that, of the wells that were drilled beyond the mean depth of the sample, only a few yielded high amounts of water, but several beyond 300 feet did (Figure 17).

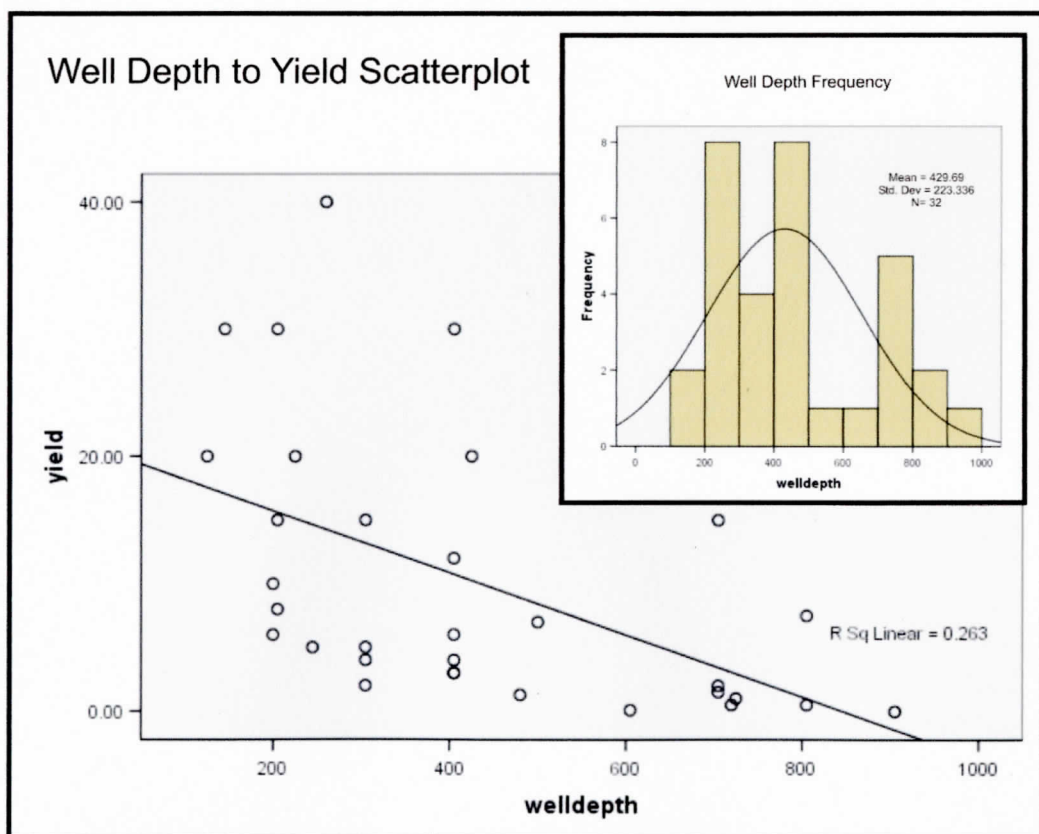


Figure 17. Random 33 Watauga wells yield to depth plot with well depth histogram.

The model also suggests a strong relationship between the yield\_trans and casing depth, which in this study was considered to be the regolith thickness of the



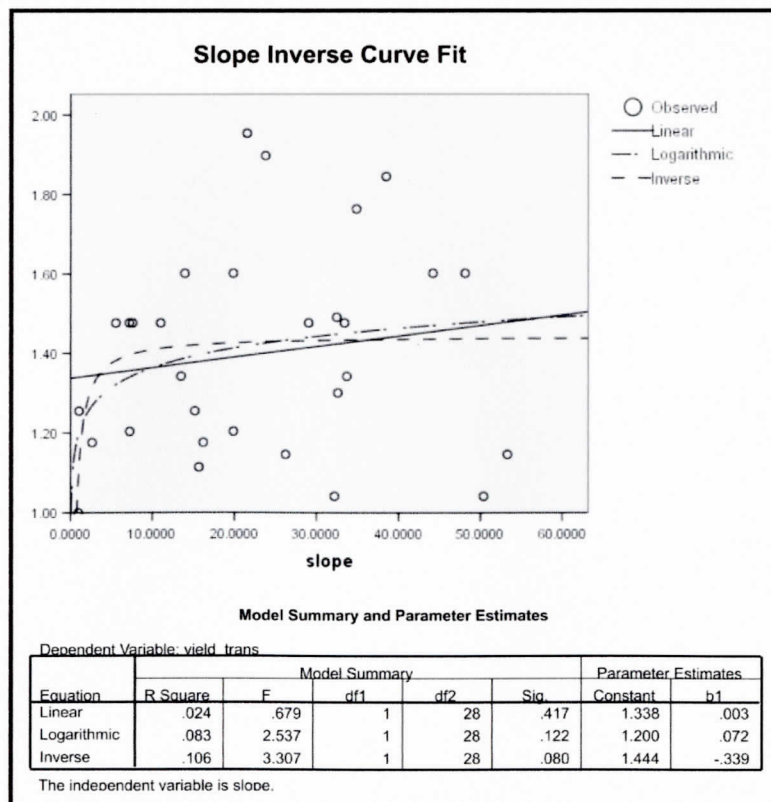
well site. Casing depth was treated separately from the combined score of topographic points and regolith points because of the interpretation of LeGrand's (1967, 2) soil thickness diagram. In the case of this study, the diagram forces the user to assign a new number to a well quantified phenomenon. This would not be the case if the regolith thickness was not known, but since this study has the advantage of better data than that of data surmised in the field, LeGrand points and regolith thickness (casing depth) were treated as separate (see LeGrand 1967, 3-4). It should also be considered that well drillers use fixed lengths of casing when in the field, and casing into the bedrock may be increased to accommodate the last length of casing.

#### *Stratified Random (Well Depth) Regression*

To be able to see a greater distribution of high depth wells in light of the Seaton and Burbey (2005) research and Daniel's (1989) suggestion, a stratified random sample was selected for another regression model. In this case, 10 wells were selected from wells with depths of 150 feet (45.72 meters) and less, 10 wells from 150 to 300 feet (45.72-91.44 meters), and the last 10 wells from those drilled above 300 feet (91.44 meters). Well depth is also a variable that is subject to limitations when used as an explanatory variable. Well depth is dependent on what depth a desirable yield is achieved when drilling, it is safe to assume when an adequate yield is found the depth of the well is not increased anymore. This is a cultural bias that Loiselle and Evans (1995) discussed at length. The dataset used in their study had the advantage of individual fracture yields as they were intersected during drilling. By using this technique they were able to eliminate the assumption that the total well depth was the actual depth at which the yield recorded was

achieved. Moore et al. (2002) get around the well depth problem via statistical methods in their study in New Hampshire. Without the aid of better data the well depth variable used in this study has explanatory limitations when considering it an independent environmental and uncontrollable variable.

Curve estimations showed linearity between the yield\_trans and well depth, the log10 of contributing area (contrib\_area\_trans), and the inverse of slope. The slope inverse (slope\_trans) was significantly linear with 92% confidence, and showed a good fit in its scatterplot (Figure 18), so was included in the regression as well. The stratified random selection of wells when modeled with linear regression further confirmed the first regression model's suggestion that shallower well depths are associated with higher yield\_trans. The model also suggests that lower slope\_trans values have a significant positive linear relationship with yield\_trans,



**Figure 18. Slope transformation.**

which was not significant in the first regression model. Higher contrib\_area\_trans values do improve the fit of the line, but do not meet the criterion of a 95% confidence interval. Together the three coefficients explain 38.8% of yield\_trans. When throwing out the statistically insignificant contributing area coefficient, the  $r^2$  value reduces to 30.0% (Table 10).

# Stratified Random Regression Model

Variables Entered/Removed<sup>b</sup>

Model	Variables Entered	Variables Removed	Method
1	slope_trans, welldepth <sup>a</sup>	.	Enter

a. All requested variables entered.

b. Dependent Variable: yield\_trans

Model Summary<sup>b</sup>

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.547 <sup>a</sup>	.300	.248	.22522	2.572

a. Predictors: (Constant), slope\_trans, welldepth

b. Dependent Variable: yield\_trans

ANOVA<sup>b</sup>

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.586	2	.293	5.777	.008 <sup>a</sup>
	Residual	1.369	27	.051		
	Total	1.956	29			

a. Predictors: (Constant), slope\_trans, welldepth

b. Dependent Variable: yield\_trans

Coefficients<sup>a</sup>

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.593	.072		22.148	.000		
	welldepth	.000	.000	-.447	-2.735	.011	.969	1.032
	slope_trans	-.421	.171	-.403	-2.465	.020	.969	1.032

a. Dependent Variable: yield\_trans

**Table 10. Stratified random preliminary tests and regression model.**



### *Analysis in the Amphibolite Region of Watauga County*

The statistical procedures for the amphibolite study area were much the same as for the whole of Watauga County, but constrained to the lithological boundary due to lineaments only being picked in this area. Only focusing on one lithology to examine lineaments and their effect on well yield avoided the potential of differing fracture patterns and more variable groundwater movement than would be with only one primary rock type. The variables that were examined in addition to the ones for all of Watauga County were 1) distance to lineament (Kim, Lee, and Lee 2004), 2) distance to lineament intersection (Kim, Lee, and Lee 2004), and 3) lineament density (ArcMap 9.3).

To begin examining the relationship of these variables, a test of normality was necessary to choose which correlations were relevant. The Shapiro-Wilk test of normality revealed most of the variables were non-normally distributed, so non-parametric tests were used to see which variables correlated to well yield. The only variables that did significantly correlate with well yield were well depth and slope as indicated by Kendall's tau and Spearman's rho non-parametric correlation tests. These were mildly negative correlations, suggesting that low slope values in the Amphibolite region of Watauga County are significantly correlated with higher well yield values. This reinforces the patterns seen for the entirety of Watauga County indicating lower well depths correlating with higher well yields. Curve estimations for the variables showed only well depth and slope to have significant linear relationships with  $\log_{10}+10$  well yield (yield\_trans) ( $\log_{10}+10$  well yield forced linearity between yield and correlated variables). The additional lineament data

variables did not have any significant linear or transformed relationships with yield\_trans so were not valid for linear regression modeling. The regression model that was performed used both well depth and slope to explain yield\_trans. Preliminary tests for 1) spatial autocorrelation via the Durbin-Watson Statistic shows no evidence for strong negative autocorrelation with a value of 1.730 and 2) multicollinearity test do not indicate multicollinearity between the two variables. (Table 11). The overall explanatory power of the regression model was only 30.1% in the amphibolite study area, with well depth being the only significant coefficient (Table 11). When the insignificant variable slope was removed well depth alone

Amphibolite Region Regression Model

Variables Entered/Removed<sup>a</sup>

Model	Variables Entered	Variables Removed	Method
1	slope, welldepth <sup>a</sup>	.	Enter

a. All requested variables entered.

b. Dependent Variable: yield\_log10plus10

Model Summary<sup>b</sup>

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.549 <sup>a</sup>	.301	.249	.19059	1.730

a. Predictors: (Constant), slope, welldepth

b. Dependent Variable: yield\_log10plus10

ANOVA<sup>b</sup>

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.422	2	.211	5.810	.008 <sup>a</sup>
	Residual	.981	27	.036		
	Total	1.403	29			

a. Predictors: (Constant), slope, welldepth

b. Dependent Variable: yield\_log10plus10

Coefficients<sup>a</sup>

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.441	.092		15.633	.000		
	welldepth	.000	.000	-.446	-2.545	.017	.844	1.185
	slope	-.004	.004	-.189	-1.076	.291	.844	1.185

a. Dependent Variable: yield\_log10plus10

**Table 11. Preliminary tests and regression model for amphibolite study area.**

explained 27.1% of the variance in yield\_trans in the amphibolite region (Table 12).

## Amphibolite Region Regression Model 2

### Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.520 <sup>a</sup>	.271	.245	.19112

a. Predictors: (Constant), welldepth

### ANOVA<sup>b</sup>

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.380	1	.380	10.404	.003 <sup>a</sup>
	Residual	1.023	28	.037		
	Total	1.403	29			

a. Predictors: (Constant), welldepth

b. Dependent Variable: yield\_log10plus10

**Table 12. Second regression model for amphibolite study area.**

No significant relationship could be found between yield\_trans and any of the lineament variables. Many studies have benefited from the inclusion of lineaments in their hydrologic study, but many have not as well (Sander 2007). The methods differ between research that employs lineaments, so certainly that could be a consideration when entertaining why this lineament study was not able to be significant enough to run through a regression model. Ideally, lineaments could be discerned for all of the lithologies in the county and analyzed separately and as a whole to explore their influence on different rock types. But as cost effective as lineaments may be, they are still time consuming, and building a working methodology for a relatively new tool in hydrologic studies would require a substantial amount of time of trial and error.



### *Statistical Conclusions*

When the linear regression model was implemented over all of Watauga County, North Carolina, the methods of LeGrand (1967), as expressed in the raster model, did not show any statistical significance, though some of the concepts that he advocated did; these being high regolith sequences and low well depths would increase the likelihood of higher yield. The second county-wide model that used only well depth and regolith thickness explained 51.4% of the variation found in well yield\_trans. This indicates that lower well depths and thicker sequences of overlying material are associated with higher well yield\_trans across Watauga County. These are concepts that LeGrand (1967) found to be significant in his own field work and attempted to quantify in his model and advocate in his USGS report (1967). His suggestion was to cease drilling at depths below 300 feet (91.44 meters), and that thicker overlying material, where he conceptualized that the highest amounts of groundwater could be found, is a plus when locating high well yield areas.

When the random sample was stratified to include shallow, moderately deep, and deep wells, lower well depths were still the most powerful explanatory variable in the model. In this case as well, regolith thickness did not play a role as in the second regression model, but was overtaken by lower slope values. Overall, the third regression model that used a stratified random sample explained 30.0% of the variation in well yield\_trans across Watauga County.

In the analysis of lineaments the study area was confined to the amphibolite lithology. None of the various lineament relationships that have been found to be significant in other studies were significantly correlated or had significantly linear

relationships to fit into a linear regression model. Instead, the same variable of lower well depths alone explained 27.1% of the variation in yield\_trans in the amphibolite region.

## Discussion

### *Raster Modeling Topographic Categories*

Implementing LeGrandian logic across all of Watauga County was an undertaking that involved interpreting the language of LeGrand's (1967) report. The regolith thickness category in his report allowed for some amount of fuzziness in scoring, but due to the benefit of well drilling records included in the Watauga Wells database, this variable was estimated within about 5 to 10 feet for each well in question. LeGrand's (1967) topographic category was not as straightforward. This involved research into what aspects of landscape dictated the appropriate classification. Speight's Landform manual is a detailed explanatory tool that was used for the thresholds between slope classes and also the fulcrum logic of the Landform 2 software in which Klingseisen, Metternicht, and Paulus (2008) distinguished one basic landform from another, which was used in this research as well. Each topographic characteristic used to model LeGrand's (1967) topographic categories in the raster form was a facet assembled in order to produce a non-biased interpretation of what he seemed to be referring to. Though two more categories were added to improve the basic logic of the raster model, the considerable amount of overlap between each raster layer in the model left some interpretation to be decided upon (Appendices A & B).

The classification of the unique raster combinations could be debatable from two standpoints. First, there could be differing opinions of how and why the combinations were calculated in the GIS environment. The landforms layer created by Landform 2 (Klingseisen, Metternicht, and Paulus 2008) primarily employed



more abstract concepts such as relief and elevation percentile which were quantified in raster logic by Wilson and Gallant's Terrain Analysis (2000) text; inherently these large swaths of differing landform territory would be home to an array of different slope and curvature values. This is logical due the large amount of area (150 meter radius) that concepts such as local relief and elevation percentile use, as compared with the very local function of slope and curvature (3x3 pixel window). So a given landform category such as a ridge area would not only have low slope gradient values representing the crest, but also include areas that begin to give way to steep slope values as the upper slope landform boundary becomes more prevalent. Similarly, the ridge area, defined by higher elevation percentile values and positive curvature would have some degree of concavity to it in small areas as well. This is handled by Landform 2 via noise reduction, but is apparent again when re-introducing curvature to the area in question upon combining the different raster products for LeGrandian topographic representation. The ridge area in question may have some amount of concavity, but does that justify it being classified as another landform, in this case possibly a depression?

The second debate for the raster interpretation could be the discounting of the researcher's ability to make decisions based on their experience and knowledge as to what should justify an area's classification. Klingseisen, Metternicht, and Paulus (2008) discussed the possible differences between automated software classification and that of an expert. There are drawbacks on both camps; the software's automated classification lacks any logic outside of what is written into its code, and an expert lacks the ability to precisely quantify topographic features such as slope. The result

of landform processing using raster logic is a very methodical and general interpretation of the landscape's geomorphology. I would argue that the measures and interpretation of earth's surface in the raster environment could be superior to that of a person's interpretation while on the landscape or when referencing a topologic data product, though not a complete substitute. It would be impossible to account for every idiosyncrasy of the landscape as methodically and precisely as computers relying on heavily researched human concepts and logic could. This notion is not disregarding human cognition of the landscape, but advocating for a robust extension of human interpretation of it. So combining the powerful and replicable nature of computer processing (Landform 2), and the logic and experience of the researcher or expert (see Geomorphometric Results and Discussion section) can result in a good interpretation of LeGrandian topographic categories.

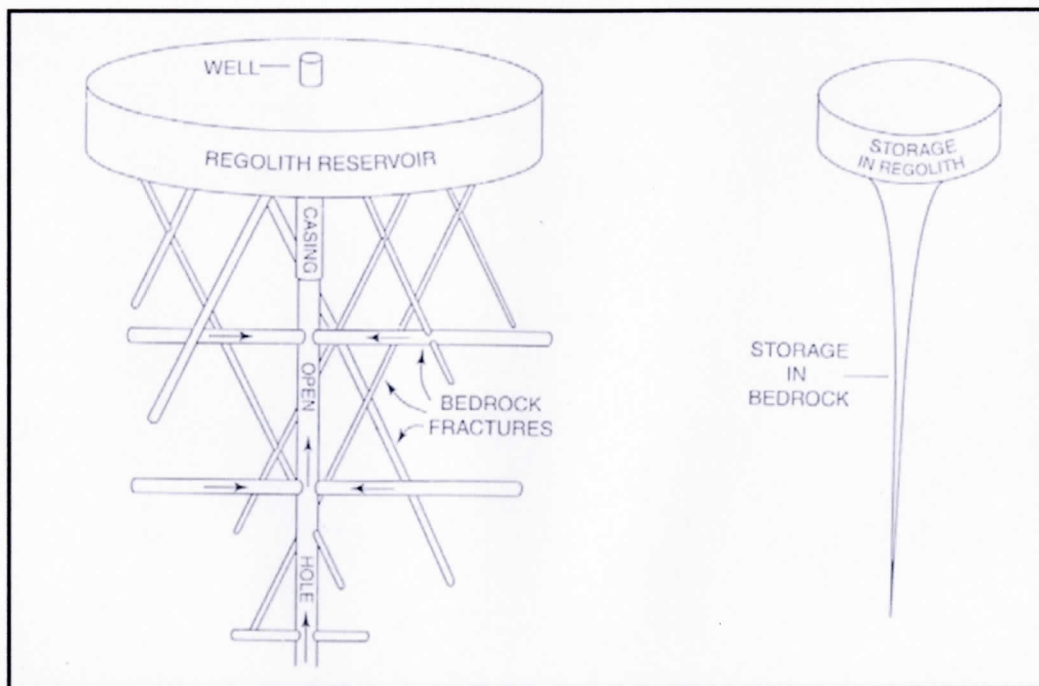
### *Statistical Modeling*

The statistical analyses shed light on some the independent environmental factors that influence yield\_trans of wells across Watauga County. The most prevalent variable that influenced yield\_trans was the well depth. In all of the regression models low drilling depths explained higher yield\_trans value; this included a stratified random sample with an equal sampling of high depth wells. This agrees with LeGrand's (1967) recommendation of ceasing drilling after about 300 feet (91.44 meters). This outcome should be considered with the knowledge of the sensitivity of well depth to human bias, given the limitations of the well database used in the analyses (Loiselle and Evans 1995; Moore et al. 2002). At the same time the research of Seaton and Burbey (2005) suggests higher well depths could turn out

to be very productive if they intersect with the ubiquitous thrust faults found in the Blue Ridge Province. The stratified random sample took 10 wells from those drilled to depths of less than 150 feet (45.72 meters), 151-300 feet (46.02-91.44 meters) and more than 300 feet (91.44 meters). The Watauga Wells Database has a majority 411 well data that are drilled to over 300 feet out of the entire 629 wells. So by looking at those numbers one might assume a more than fair representation of deep wells that potentially could add to Seaton and Burbey's (2005) research argument. But the well depths that Seaton and Burbey (2005) were referring to were those up to 300 meters or 984.24 feet; the Watauga Well's database only has 17 wells close to that deep. So, despite an attempt to explore Seaton and Burbey's (2005) research findings, it appears that the database may not represent a conclusive portion of high depth wells that Seaton and Burbey found to be hydrologically significant.

The other variable that significantly explained variation of yield\_trans values for the whole of Watauga County was regolith thickness, which also reinforces LeGrand's (1967) model. This is plausible when considering the basic hydrology of the area. Sequences of regolith in the Blue Ridge are much less than those in the neighboring Piedmont Province, which LeGrand (1967) designed his model to include. Though LeGrand (2004) conceptualizes the regolith layer as having the most amount of storativity (Figure 19), most of the wells drilled in Watauga County obtain desired yield from bedrock fractures (Wright Jr. 2009, personal communication). So if the regression model suggests that higher regolith sequences are beneficial for well yields, then perhaps regolith in Watauga County foregoes acting as the main storage medium, to serve as a medium that increases





**Figure 19. Conceptual model of water storage in fractured bedrock aquifers from LeGrand (2004) (Heath 1980).**

transmissivity to the bedrock fractures below. In other words, the greater the volume of material to transmit intercepted water, the higher well yields are likely to be. Seaton and Burbey (2005) discuss the intercepted through-flow water that well drillers encounter in the regolith layer as “first water” (310). This water being through-flow does not yield any significant amount of sustained groundwater. By examining the wells dataset, it is possible to confirm whether significant yield is achieved in the regolith layer or in the bedrock. If a high amount of groundwater was yielded before extending the borehole much past the bedrock interface, the well driller would cease drilling and confirm LeGrand’s regolith storage concept; if drilling continued past the wells that had high casing depths and high well yields then the subsequent yield reported could reasonably be associated with the fractures in the bedrock interface. In the random sample of Watauga County the 11 (out of 33) highest yielding wells’ casing depths and drilling depths were plotted together. The

resulting scatterplot shows that of the highest yielding wells in the sample, many wells' boreholes continued well past the regolith interface into the bedrock where they achieve the desired high yields (Figure 20). This is common for this area, where a local well driller's rough estimate for wells yielding desired amounts in the bedrock is about 80% (Wright Jr. 2009, personal communication).

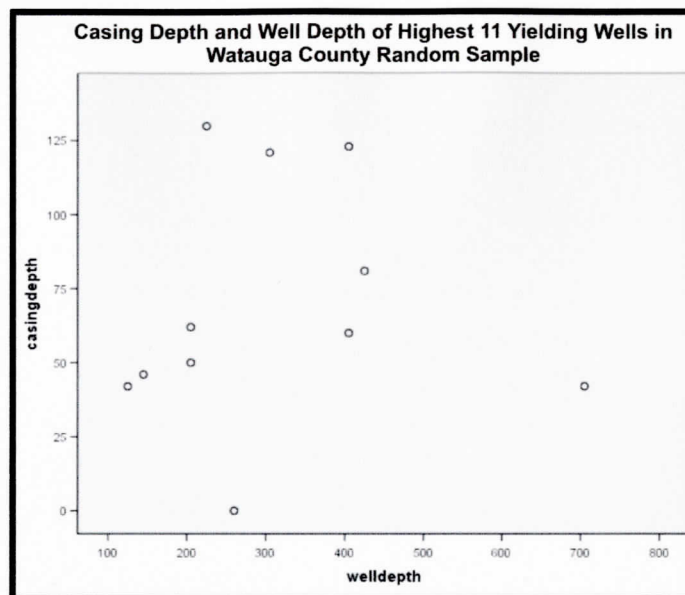


Figure 20. Casing depth to well depth plot in high yield wells.

### *Regression Modeling Integrating Lineaments in the Amphibolite Region*

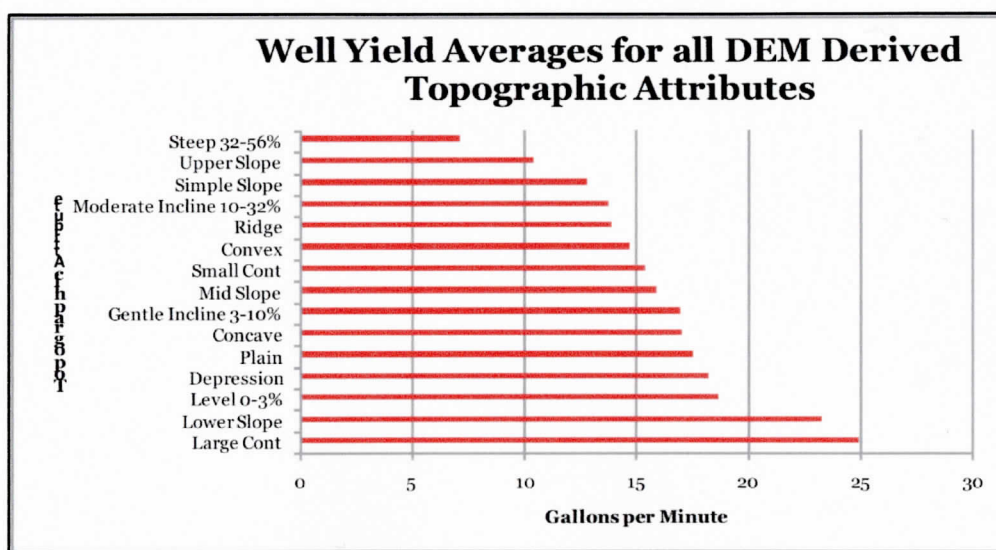
The various relationships of lineaments to the randomly selected wells in the amphibolite region of Watauga County did not have any significant correlation nor linear relationship with well yields or well yield\_trans. One could conclude from this that lineament discernment is not a useful technique in Watauga County with regard to explaining well yield. Other avenues of research could be to analyze lineaments with respect to azimuth orientation, or to examine fracture correlated lineaments. Given the ease of digitizing and producing lineament maps, a next logical step could be exploring different digitization techniques and possibly differing methods as

where to digitize e.g. single out ridge line and other convex feature lineaments from lineaments expressing depressions and valleys, or using different imagery such as described in Chapter 4. LeGrand (1992) contested this as the same as the topographic method, but given the amount of time and computing power it takes to model his topographic categories as compared to digitizing lineaments, though they both may be a means to the same end, lineaments may be a more viable avenue. These avenues and others should be pursued given the small amount of time and GIS capabilities that digitizing lineaments requires as compared to raster modeling landforms.



## Final Analysis and Creation of MOD2

Figure 21 shows that overall the highest average well yields across Watauga County in the landform category were found at 1) Lower Slopes (23.25 gpm), 2) Depressions (18.23 gpm), and 3) Plains (17.70 gpm). The highest slope category well yields were found in 1) Flat areas (0-3%), 2) Gentle slopes (3.1-10%), and 3) Moderate slopes (10.1-32%), with average well yields at 18.63, 16.98, 13.75 gpm, respectively (Figure 21). Expanded hierarchies of each topographic attribute category can be found in appendices C, D, E, and F; also included are the percentages of wells that fell within given yield ranges with respect to individual topographic attributes



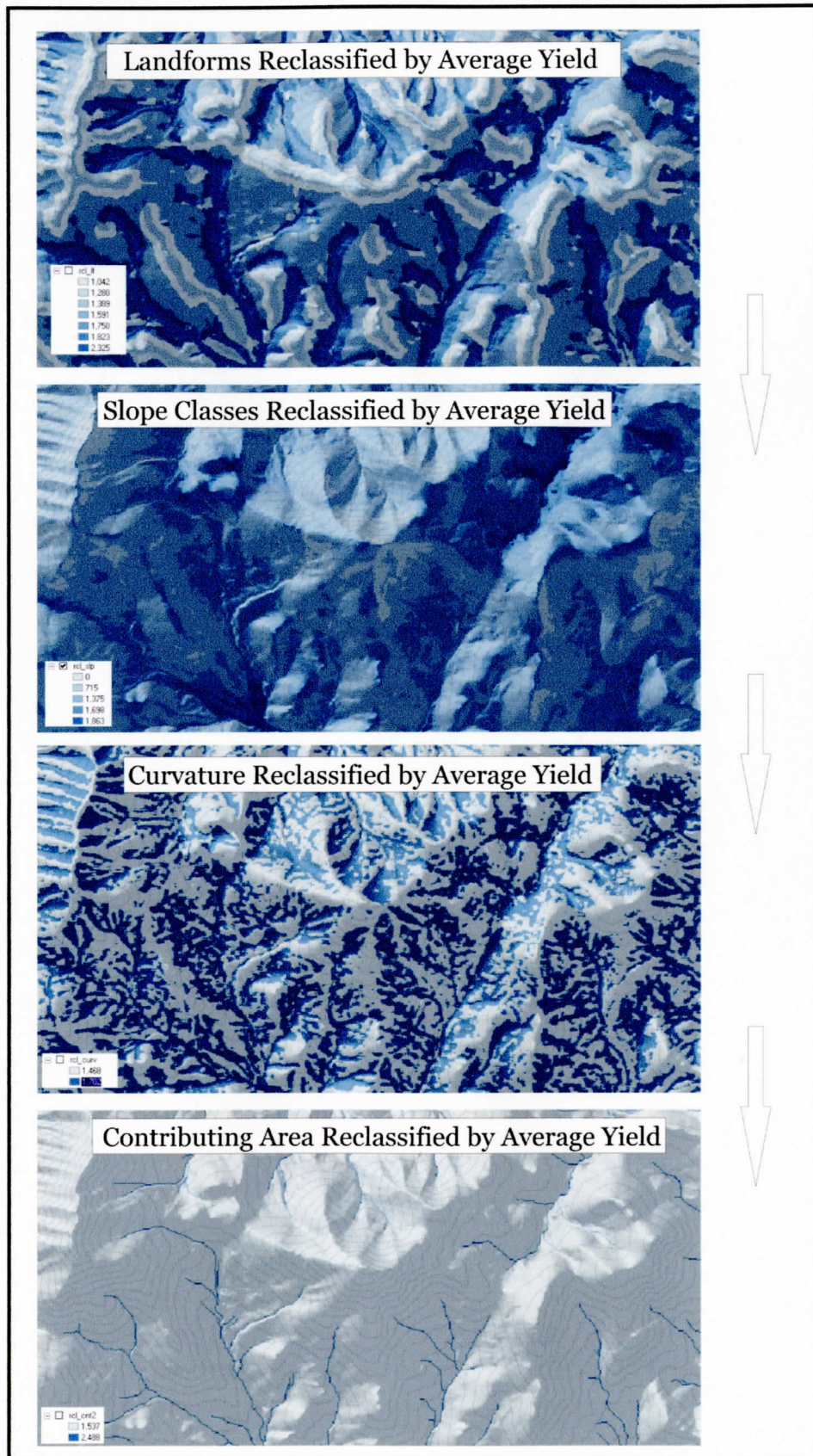
**Figure 21. Average yield of Watauga wells database sorted by DEM processed topographic attributes that are most hydrologically significant.**

(Appendices C, D, E, and F). The mean contributing area for the county is about 12.5 square kilometers. Wells with less than that amount of contributing area yielded on average 15.37 gpm, areas with more than the mean contributing area yielded on average 24.88 gpm. Areas that were classified as concave on average yielded 17.02 gpm and those that were convex averaged 14.08 gpm.

To advance the numerical relationships shown in Figure 21 that are based on actual well yield data, another raster model termed MOD2, was created using the differences in averages shown in Figure 21. Since the whole of Watauga County was already processed for each of the DEM derived topographic attributes shown previously, assigning each swath of territory the mean of the well data contained within it was a logical next step when looking at the ranking of all the DEM derived topographic attributes together. The goal here was to come to a meaningful conclusion as to how a GIS could potentially aid in explaining groundwater occurrence.

The combination of the various different topographic attribute categories was much the same as explained in the geomorphometric analysis section. The difference was in the logic of assigning the numeric values to raster data. To model the LeGrand (1967) hydrologic model, all of the topographic attributes were combined pixel by pixel and after summation were categorized into a LeGrandian value that each pixel combination seemed to fit into. When creating MOD2, the average yield data used in Figure 21 were assigned to each topographic attribute swath for all of Watauga County. For example, the landform category “ridges” had an average well yield of 13.89 gpm, in the raster logic the entire area classified as a ridge was assigned 1389 as its identifying value; “simple slopes” mean value was 12.80 gpm, so its new value was 1280. This system of reclassification satisfies raster logic by differentiating areas by numerical values, as well being scientifically sound due to the new values and differences between each value being based on real data (Figure 22). The result was four different raster products that had various numerical values based on their

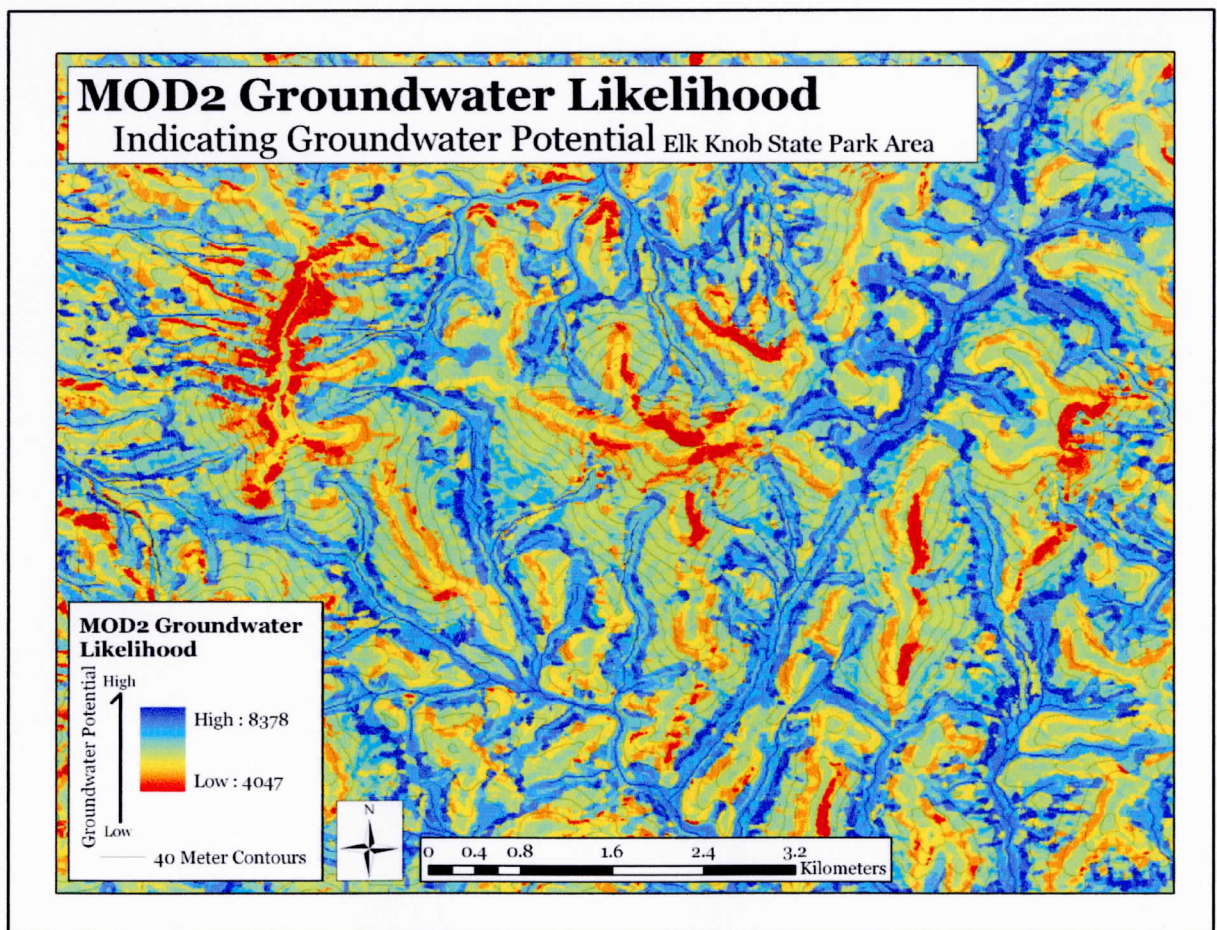




**Figure 22. Flow Chart for MOD2 Raster Combination.**



average recorded yield. To utilize all the available topographic attributes, Landforms, Slope Categories, Curvature, and Contributing area were summed for the final raster data product (Figure 23). The outcome is a gradient of groundwater likelihood based on the wells database for the whole of Watauga County. The numbers themselves cease to be “real” numbers after this summation, as only their numerical relationship to each other can be considered “real”. For instance, the landform raster map when represented by its averages can be considered a valid numerical representation of well yield. Once those values are combined with the slope categories average yield, the final product of those summations is no longer considered an actual number based on yield; the relationships with each other (the distance between means) with



**Figure 23. MOD2.**

respect to Figure 21 are very real but the actual numbers in the combined continuum of groundwater likelihood is arbitrary. For that reason and more, this data product is not overly sophisticated or predictive with regard to well yield, but it is based on real well data and can be considered a valid representation of how groundwater is spatially distributed in Watauga County. Though the mean well yields by topographic attribute will certainly vary by location, this procedure could be carried out for any study area in question in the Blue Ridge, to investigate what are the most significant topographic attributes that influence groundwater in a given area, and aid in finding higher well yields in areas yet to be drilled for groundwater.



## **Summary**

To analyze the complex groundwater system in Watauga County North Carolina, the model described by LeGrand (1967) and referenced by numerous others was implemented. The familiar, but nonetheless elusive terms that describe LeGrand's (1967) topographic categories were quantified and represented in a GIS environment using geomorphometric methods that could be replicated by any GIS user with relative ease. The second, regolith thickness category was derived from the Watauga Wells Database (Brad Huffman, US Geological Survey, October 2007, Phone Interview) attribute "casing thickness"; the Watauga Wells Database was also used for testing purposes with the LeGrand (1967) model's predicted well yield values. By checking a number of the locations of wells in the field, they were found to be accurate with regard to the scale of this model and therefore their locations were assumed to be valid for this study.

To analyze groundwater yields in conjunction with 1) the LeGrand (1967) groundwater model, as well as 2) other environmental attributes readily available to the earth science researcher, statistical analyses were implemented to examine which environmental factors best predict variation in well yield across the county. For the whole of Watauga County each well site's attribute data were appended with 1) LeGrand points (LeGrand 1967; Speight 1990; ArcMap 9.3; Klingseisen, Metternicht, and Paulus 2008), 2) Slope Percentage (ArcMap 9.3), 3) Landform Category (Klingseisen, Metternicht, and Paulus 2008), 4) Contributing Area (ArcMap 9.3) and 5), Curvature (ArcMap 9.3). When a random sample of 33 wells in Watauga County was taken and analyzed, well yield\_trans had significant linearity with well depth,



casing depth, LeGrand points, and slope. A linear regression model found that of the four variables, shallower well depths and higher casing depths explained 51.4% of the variation in well yield\_trans.

A second regression model was assembled that used a stratified random sample of wells from low (less than 150 feet [45.72 meters]), moderate (151-300 feet [46.02-91.44 meters]) and high (more than 300 feet [91.44 meters]) drilling depths to further examine the work of Seaton and Burbey (2005) which was contrary to LeGrand's (1967) concept of conductive fractures pinching out at depths greater than 300 feet (91.44 meters) (Daniel 1989). This stratified random linear regression model showed again that lower well depths accounted for higher well yield\_trans. The stratified random sample also indicated that lower slope\_trans values significantly explained differing values in well yield\_trans, for a total of 30.0% explanation of variance.

To explore the frequently used technique of picking lineaments and relating their attributes to well yield, lineaments were discerned by two different researchers for the amphibolite region in Watauga County. These were digitized in the GIS environment using topographic contour lines 1:48,000 and 1:24,000 scales. Lineaments that were used coincided within a fuzzy tolerance distance of 75 meters between each of the picks by the researchers. In addition to the appended attribute data described above for the whole of Watauga County, each well in the amphibolite area also received data regarding the described different aspects of its relationship to lineaments in its immediate area. This included 1) Distance to Nearest Lineament 2)

Distance to Nearest Lineament Cross-Section 3) and Lineament Density within a 500, 750, and 1000 meter search radius.

Statistical analysis revealed that yield\_trans was significantly correlated only with well depth, and slope percentage. Linear regression revealed that lower well depths and lower slope values explained 30.1% of the variation between yield\_trans with well depth being the only significant coefficient. The second more parsimonious regression model using only well depth's relation to well yield\_trans showed that lower well depths explained 27.1% of the variation of well yield\_trans for the amphibolite region in Watauga County.

MOD2 was created using the same DEM derived coverages that were utilized for modeling the LeGrand (1967) topographic categories. The mean well yield for the various categories of the topographic attributes was used as the classifier during recombination for MOD2 in the GIS environment. The result was a raster map that represented a continuum of groundwater likelihood for Watauga County based on the wells database.

## Conclusion

Groundwater in fractured bedrock terrain is an elusive commodity that is much needed by the local human populations. This work has sought to examine with a contemporary approach basic concepts and methods that have been in use for some time as well as to look into other popular techniques that may shed light on groundwater in these terrains.

Directly modeling the landscape helped in examining the LeGrand (1967) techniques that have been in use for many decades. While the combined LeGrand results did not yield any significant statistical conclusions, when broken apart the different aspects of LeGrand's (1967) concepts became clearer. Luckily the aspects of the landscape such as low well depth, high regolith thickness, and low slope values are easier to take into account and implement than that of the LeGrand (1967) topographic model, but LeGrand's (1967) ideas of high regolith and lower well depths being good for yield appeared to be somewhat in agreement with the statistics. Though regolith sequences in the Blue Ridge are less than those in the Piedmont, the thickest regolith areas in Watauga County explained higher yield\_trans values across the area. Most of the wells in the Watauga Wells Database were over 300 feet; LeGrand (1967) advocated for wells ceasing at depths of around 300 feet (91.44 meters); though most of the wells were deeper than LeGrandian logic would approve of, the shallowest of these were the most productive.

Lineaments did not have any significant correlation or influence with yield values. While relatively easy and cost effective to implement, this study did not benefit from them. The methods of digitizing lineament can always be improved



upon and perhaps a different approach may yield better results. Lineaments methods are similar to those of LeGrand (1967) in the sense they require the user to decide what goes where. Methods of improving user-to-user agreement have been published and employed, but not exhausted in this study. Differing base imagery and standards of agreement between researchers could both be explored to further lineament study. The same could be said for LeGrandian raster modeling techniques.

This study has attempted to replicate the popular LeGrand (1967) groundwater model in an unbiased way, and explore the newer research trend of lineament analysis in fractured bedrock environments. While lineament analysis was inconclusive, the strict LeGrand (1967) scoring technique was as well. Luckily, widely available environmental tools did shed light on groundwater occurrence, mainly DEM processing which could be a means to investigate the significant regolith thickness variable, as well further the topographic attributes in Figure 22.

The methods described in this work could be applied to any other environment where fractured bedrock techniques are applicable. Whereas LeGrand's techniques are very well known, and his language familiar, replicating his techniques is a subjective endeavor that requires a high amount of guesswork for the researcher interested in exploring groundwater techniques in these types of aquifers. Conversely, the topographic attributes derived from DEMs and the logic used in combining them could be replicated verbatim anywhere in the Blue Ridge or other fractured bedrock aquifers. Sources named in this study and others describe techniques for delineating lineaments that attempt to stray from bias interpretation.

While the techniques used within are one way to utilize lineaments, there are many other approaches one could make an entire career out of researching.

MOD2 was an additional product that worked backward from lineament and LeGrand (1967) raster modeling. The wells database provided the foundation for the MOD2 raster map of groundwater likelihood for Watauga County. Though MOD2 is not predictive for “hard” numbers with respect to well yield, it does give a sense of what topographic features are the most hydrologically significant in the county. Ideally, a data product such as MOD2 could be created by any GIS user interested in groundwater yield for any fracture bedrock aquifer area, and used to aid in well sitting in the field.

Whether a researcher employs LeGrandian techniques, lineaments, or methods similar to MOD2, as long as the populations of the Blue Ridge Region and other fractured crystalline bedrock aquifers require water, there will be a need to better understand the resources that provide them. Polarization by schools of thought or techniques and fervor for one’s specialty will only limit progress in understanding these complicated aquifers and how they function. More likely, a greater cognizance will be achieved through comprehensive earth science research to meet the needs of the current and future larger populations.



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## APPENDIX A

### **LeGrand Raster Logic 1**



## APPENDIX B

### **LeGrand Raster Logic 2**

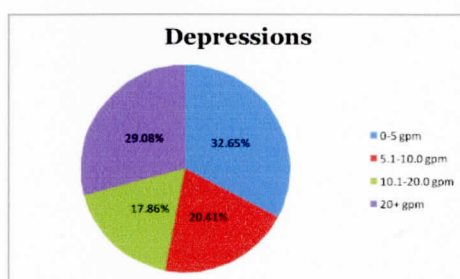
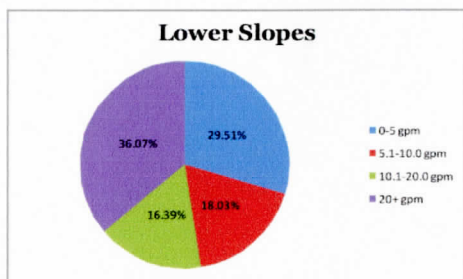
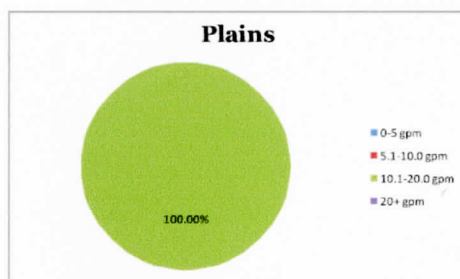
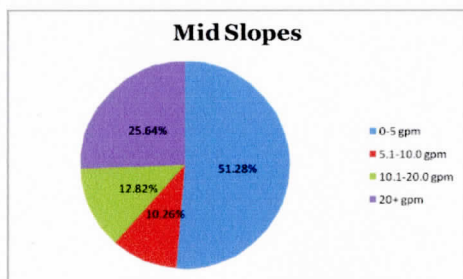
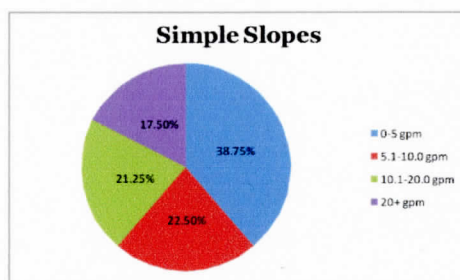
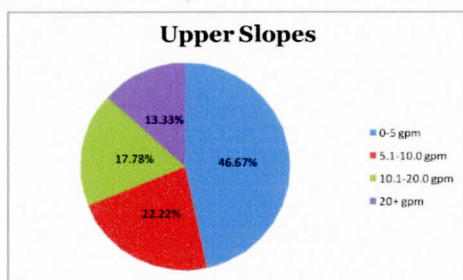
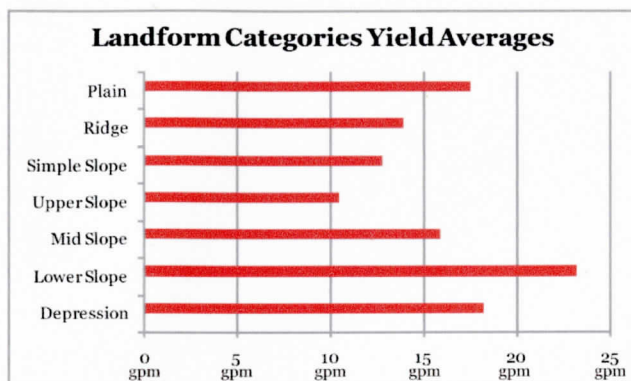
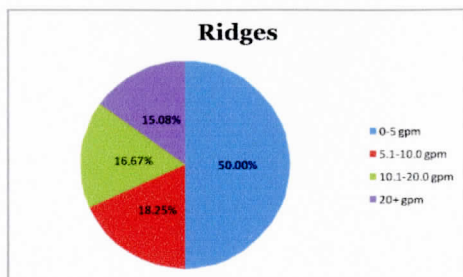




## APPENDIX C

### **Landform Well Yield Hierarchy and Range Percentages**

## Percent of Wells within 0-5, 5.1-10, 10.1 - 20, and 20+ Gallons per Minute: Landforms

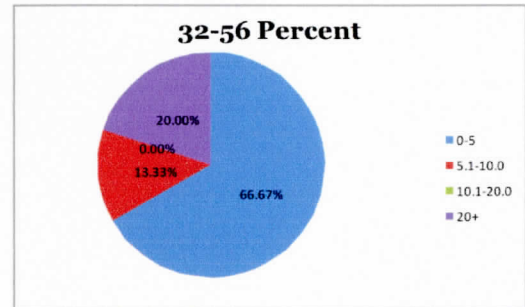
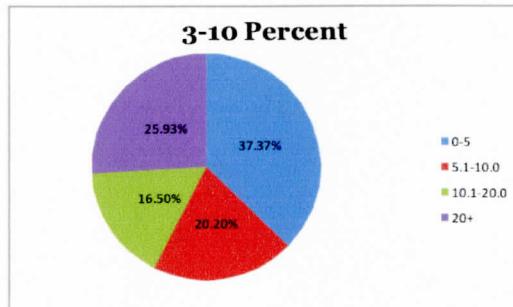
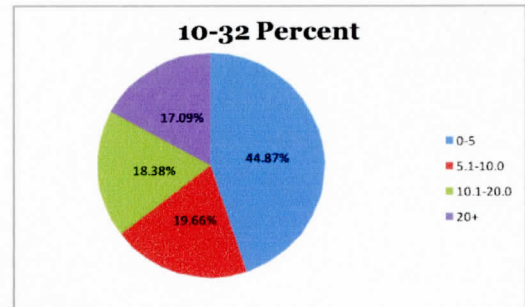
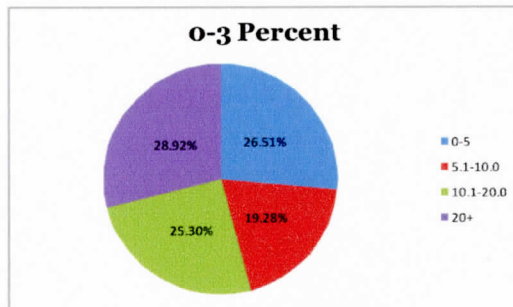
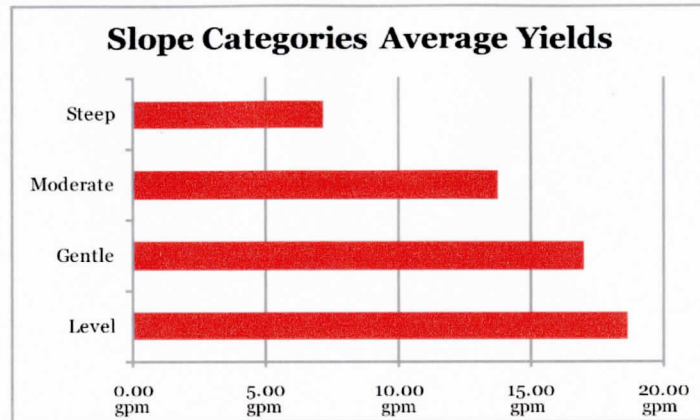




## APPENDIX D

### **Slope Well Yield Hierarchy and Range Percentages**

## Percent of Wells within 0-5, 5.1-10, 10.1 - 20, and 20+ Gallons per Minute: Slopes

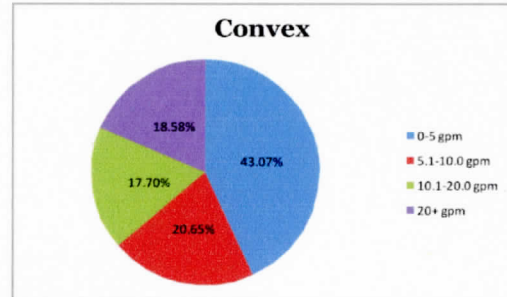
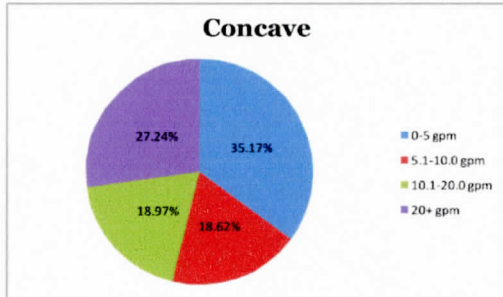
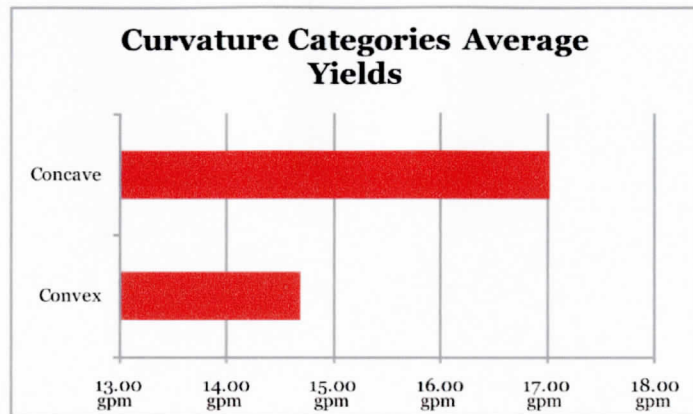


## APPENDIX E

### **Curvature Well Yield Hierarchy and Range Percentages**



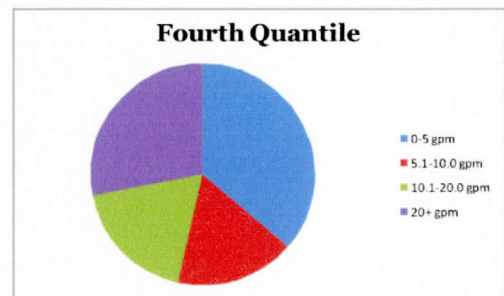
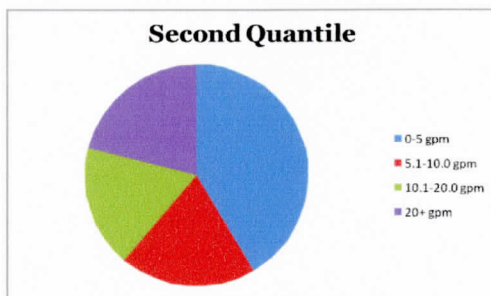
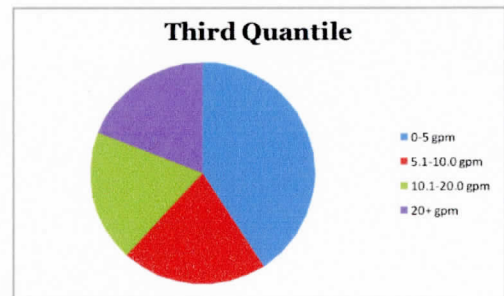
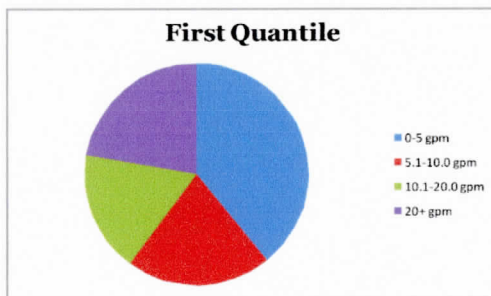
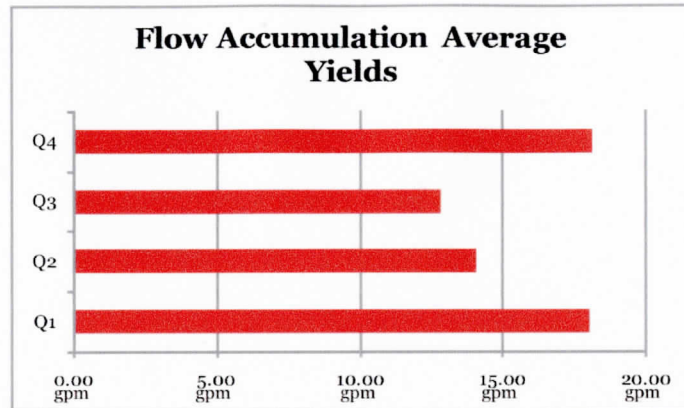
## Percent of Wells within 0-5, 5.1-10, 10.1 - 20, and 20+ Gallons per Minute: Curvature



## APPENDIX F

### **Flow Accumulation Well Yield Hierarchy and Range Percentages**

## Percent of Wells within 0-5, 5.1-10, 10.1 - 20, and 20+ Gallons per Minute: Flow Accumulation





### **Biographical Sketch**

Williams Coker Gandy was born in Los Angeles, California, on October 15, 1983. When he was five his family moved to Blowing Rock, North Carolina where he attended elementary school. He graduated from Watauga High School in June of 2002, and entered Appalachian State University that August. In August of 2006 he graduated with a Bachelor of Science degree in Community and Regional Planning and another in Geography. He was accepted to the Appalachian State's Geography department graduate program in August of 2007 where he pursued a Master of Arts degree that was completed in August of 2009.

His permanent mailing address is 2166 George Hayes Road, Boone, North Carolina 28607. His parents are Mr. and Mrs. Harry and Debra Gandy of Boone, North Carolina.